CRANFIELD UNIVERSITY

Diogenes Luis Antille

Formulation, utilisation and evaluation of organomineral fertilisers

School of Applied Science

Engineering Doctorate Thesis

Supervisors:

Prof R J Godwin

Dr R Sakrabani

4 March 2011

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Engineering.

ABSTRACT

The water industry recognises significant cost advantages in recycling sewage sludge (biosolids) to agricultural land compared with alternative more expensive disposal options such as incineration or landfill. A recent technique was proposed by United Utilities plc for the production of organomineral fertilisers (OMF) from biosolids granules which adds additional nitrogen to the biosolids' nutrients to form a balanced NPK fertiliser. The aim of this research was to determine the effects in cereal and grass crops of using organomineral fertilisers (OMF) made from nutrients-enriched biosolids granules and to contribute towards the understanding of nutrient management and dynamics in agricultural systems. The research included soil incubation, glasshouse, lysimeters and field studies which used winter wheat (*Triticum aestivum L.*) and ryegrass (*Lolium perenne L.*). A theoretical model was developed for fertiliser particle distribution studies which required the determination of key physical properties of the products. Two OMF formulations have been suggested: OMF_{10} and OMF_{15} which have the following NPK compositions: 10:4:4 and 15:4:4 respectively. These were suggested for use in grassland as well as arable cropping. The particle trajectory model showed that the particle size range for OMF_{10} and OMF_{15} should be between 1.10 and 5.50 mm and between 1.05 and 5.30 mm in diameter respectively. The incubation studies showed that the greatest rate of nitrogen release from OMF_{15} (% total-N applied) occurred in the first 30 days following soil application (range of *c.*40% to 70%) with a further *c.*10% to 25% in the following 60-90 days depending on the soil type. The glasshouse studies showed that grass responses to nitrogen were initially in the range of 14 to 20 kg [DM] ha^{-1} per kg of additional nitrogen but they decreased by *c.*40-50% in 2008 and 2009. In the field studies, mean grain yields of winter wheat were *c.*7815 kg ha^{-1} (OMF_{10}) and *c.*8600 kg ha^{-1} (OMF_{15}); these were approximately 11% and 23% higher than biosolids- and between 30% and 20% lower than urea-treated crop respectively. The most economic rate of nitrogen application (MERN) for winter wheat, across the four crop seasons, were 257 and 248 kg [N] ha^{-1} with the use of OMF_{10} and OMF_{15} respectively. The use of OMF did not change soil extractable-P levels significantly in both the field and glasshouse experiments; hence, soil-P indexes remained closed to constant which was therefore supporting the reasons for the initial formulations. There is a need to improve the quality control for physical and chemical properties of OMF and to conduct spreading tests that may enable application at 18 or 24 m wide tramlines. The logistics of applying a straight nitrogen source as the first fertiliser dressing (late February to middle of March), and the balance of the application with OMF approximately 30 to 40 days later (early April) should be considered. Given the characteristics of the yield to nitrogen response curves, it is unlikely that OMF can be competitively priced. If the gross margin received by the farmer is to be unaffected by the fertiliser choice, the product will need to be subsidised. Given the assumptions made in the scenario it would be still an economic proposition for United Utilities plc to do this when compared with the costs of other disposal options. From this, there appears to be potential for further development of OMF products.

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"…this opens up the whole issue and the silly debate about organic fertilizers versus inorganic. I have always said, use all the organic fertilizer that is available but don't mislead the world into believing that it is possible to produce all the food that we need for this 6.1 billion people with organic fertilizers only…without fertilizers the whole world would be in complete disorder, we couldn't produce our food…"

N E Borlaug [1914-2009]
(On organic versus inorganic fertilizers)

To Josefina and Dio

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NOMENCLATURE

A_E:	Agronomic efficiency of applied nitrogen.
Al:	Aluminium.
AN:	Ammonium nitrate fertiliser.
ANOVA:	Analysis of variance.
ASABE:	American Society of Agricultural and Biological Engineers.
ASAE:	American Society of Agricultural Engineers.
ATP:	Adenosine tri-phosphate.
B_0:	Bid amount.
B_E :	Break even.
B_i:	Bid amount (initial).
B_{Hi}:	Bid amount (highest).
B_j:	Bid interval.
B_{Li}:	Bid amount (lowest).
BDL:	Below detection limit.
BRIC:	Brazil, Russia, India, China.
°C:	Degrees Celsius.
C:	Carbon.
C:N:	Carbon to nitrogen ratio.
Ca^{2+}:	Calcium.
CAN:	Calcium ammonium nitrate.
C_{OMF}:	Cost of spreading OMF.
C_{Urea}:	Cost of spreading urea.
Cd:	Cadmium.
C_D:	Drag coefficient (also C_d).
CEC:	Cation exchange capacity.
C_F:	Cost of fertiliser.
CH_4:	Methane.
CIWEM:	Chartered Institution of Water and Environmental Management.
CO_2:	Carbon dioxide.
Cont'r:	Contractor.
C_S:	Cost of spreading.
Cu:	Copper.
cv:	Variety (crop).
CV:	Coefficient of variation.
$\Delta\bar{Y}$:	Differential yield.
D_{10}:	Percentile (10%) – granulometric distribution curve.
D_{16}:	Percentile (16%) – granulometric distribution curve.
D_{50}:	Percentile (50%) – granulometric distribution curve.
D_{84}:	Percentile (84%) – granulometric distribution curve.
D_{90}:	Percentile (90%) – granulometric distribution curve.
$d^{o}C$:	Degrees day.
DAP:	Di-ammonium phosphate.
DM:	Dry matter yield.
DS:	Dry solids content.
ε_P :	Elasticity of demand.
EngD:	Engineering Doctorate Programme.
EPSRC:	Engineering and Physical Science Research Council.
Ext-P :	Soil extractable phosphorus – Olsen's-P.
Fe:	Iron.
$FeCl_3$:	Iron chloride.
FYM:	Farm yard manure.
GI:	Gross income.
GM:	Gross margin.

g pot^{-1}:	Grams per pot.
GSI:	Granulometric spread index.
GWP:	Global warming potential.
H:	Hydrogen.
ha^{-1}:	per hectare.
HCO_3^- :	Hydrogen carbonate.
Hg:	Mercury.
HGCA:	Home Growth Cereal Authority.
IFA:	International Fertiliser Industry Association.
IFDC:	International Fertiliser Development Centre.
IFPRI:	International Food Policy Research Institute.
IFS:	The International Fertiliser Society.
I_P:	Partial factor productivity of applied nitrogen.
IPCC:	Intergovernmental Panel on Climate Change.
K:	Potassium.
K_2O:	Potash.
kg:	kilogram.
kg ha^{-1}:	kilograms per hectare.
kg m^{-3}:	kilograms per cubic metre.
kPa:	kilopascal
KTP:	Knowledge Transfer Partnership.
LIFFE:	London International Financial Future and Options Exchange.
$LSD_{[5\% \text{ level}]}$:	Least significant differences (5% level).
m:	Meter.
m^2:	Square meter.
m^3:	Cubic meter.
m s^{-1}:	Meters per second.
MAP:	Mono-ammonium phosphate.
max-min.rep:	Differences between the maximum and the minimum number of replicates.
max.rep:	Maximum number of replicates.
MERN:	Most economic rate of nitrogen (derived from the response curves).
Mg:	Magnesium.
mg kg^{-1}:	Milligrams per kilogram.
mg l^{-1}:	Milligrams per litre.
min.rep:	Minimum number of replicates.
n	Number of observations.
N:	Nitrogen.
^{15}N:	Nitrogen (15-isotope).
$\overline{N}$:	Mean nitrogen rate.
N_{max}:	Maximum nitrogen application rate (derived from the response curves).
N:P:	Nitrogen to phosphorus ratio.
N_2O :	Nitrous oxide.
N_{10}:	Nitrogen application rate equivalent to Y_{10} (derived from the response curve).
NH_2 :	Amine.
NH_3	Ammonia.
$NH_4^+ - N$:	Ammonium nitrogen.
$NH_3 - N$:	Ammonia nitrogen.
NABIM:	National Association of British and Irish Millers.
NADP:	Nicotinamide adenine dinucleotide phosphate.
NO_3^- :	Nitrate.
NO_2^- :	Nitrite.
NPK:	Compound fertiliser containing nitrogen, phosphorus and potassium.

N_{Rate}:	Nitrogen application rate.
NUE:	Nitrogen use efficiency.
NVZ:	Nitrate Vulnerable Zones.
OECD:	Organization for Economic Cooperation and Development.
OMF:	Organomineral fertiliser.
OMF_{10}:	Organomineral fertiliser containing 10% N, 4% P_2O_5 and 4% K_2O.
OMF_{15}:	Organomineral fertiliser containing 15% N, 4% P_2O_5 and 4% K_2O.
ρ_b:	Bulk density.
$\%P_{available}$:	Percentage available phosphorus (as % of total phosphorus applied)
P:	Phosphorus.
P_2O_5:	Phosphate.
Pb:	Lead.
P_C:	Price of the grain or the crop.
ΔP:	Percentage change in price.
ΔQ:	Percentage change in demand
£ ha^{-1}:	Pounds per hectare.
£ kg^{-1}:	Pounds per kilogram.
£ t^{-1} :	Pounds per tonne.
P_N:	Price of nitrogen.
ppm-v:	Part per million by volume.
p:	probability (F probability).
Q:	Demand.
OSR:	Oilseed rape.
R_N:	Apparent nitrogen recovery.
R_P:	Price ratio.
rpm:	Revolutions per minute.
s	seconds.
SD:	Standard deviation.
SOM:	Soil organic matter (%).
SMN:	Soil mineral nitrogen.
SNS:	Soil nitrogen supply.
SO_2:	Sulphur dioxide.
SO_3:	Sulphur trioxide.
SSP:	Single superphosphate.
T:	Time.
t m^{-3} :	Tonnes per cubic meter.
TN:	Total nitrogen.
TN_{grain}:	Total nitrogen in grain.
$TN_{off\text{-}take}$:	Total nitrogen off take by the crop.
TN_{plant}:	Total nitrogen in plant material.
TN_{soil}:	Total nitrogen in soil.
TN_{uptake}	Total nitrogen uptake.
t_{pr}:	Probability of t-value (probability for the estimate of parameter).
TON:	Total oxides of nitrogen.
TSP:	Triple-superphosphate.
TVC:	Total variable costs.
UAN:	Urea ammonium nitrate – solution (33% N).
W_{1000}:	Weight of one thousand grains.
WTP:	Willingness to pay.
$\overline{Y}$:	Mean yield.
Y_{10}:	Optimum yield (derived from the yield to nitrogen response curves).
Y_{max}:	Maximum yield (derived from the yield to nitrogen response curves).
Y_{MERN}:	Yield corresponding to MERN (derived from the yield to nitrogen response curves).
Zn:	Zinc.

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

1.1 Overview of current situation

Sewage sludge (biosolids) is an inevitable by-product resulting from the sewage treatment process. In 2005, a total of 1.4 million tonnes of sewage sludge (dry solids basis) were produced in England and Wales and it is estimated that this figure will increase to *c*.1.6 million tonnes by 2010 (Defra, 2007a). This projected increase in sewage sludge production responds mainly to the growth of the population and the continuous adoption of cleaner technology needed to comply with stringent requirements for the treatment of sewage effluents. UK population, presently 61.4 million, has increased on average by *c*.0.5% per year since 2001 (ONS, 2009) resulting in larger number of households being connected to the sewerage system. Further requirements for the treatment of sewage effluents could arise from future designations of sensitive waters under the specifications outlined in the EU Urban Wastewater Treatment Directive 91/271/EC (Edge, 1999). The use of tertiary treatment, which is performed for the removal of nutrients from wastewaters, can significantly increase sludge production. Tertiary treatment is required before treated water is recycled to the environment in sensitive areas (Defra, 2002) and it is estimated that removal of phosphorus by precipitation increases sludge production by approximately 10% to 25% (Edge, 1999).

In England and Wales, the disposal of sewage sludge follows a number of routes which include, most importantly, recycling to farmland (72%), incineration (18%), land reclamation and restoration (6%) and landfill (1%) as reported by Defra (2007a). The disposal of sewage sludge is a highly regulated activity (Evans, 1998) and current legislation restricts the opportunities for disposal (Moseley et al., 1998; Moseley, 1999). The disposal at sea was banned as of 31st December 1998 through the Urban Wastewater Treatment Regulations 1994 which implement the EU Urban Waste Water Treatment Directive 91/271/EC (CEC, 1991a). Similarly, the EU Landfill Directive 99/31/EC (CEC, 1999) has virtually closed the landfill route for disposal since a reduction in the amount of biodegradable waste equivalent to 75% of that landfilled in 1995 is required by 2010 with further reductions to be enforced thereafter (Defra, 2003; Defra, 2007b). Incineration appears to be difficult to justify; firstly, because it is not in line with the intention of the UK Government of cutting back CO_2 emissions by 20% in 2010 (Defra, 2007c). Secondly, it may become economically unsustainable in the long term as more incineration capacity would be needed to deal with increasing sludge production.

The expansion of existing incineration infrastructure can be cumbersome as obtaining planning permissions is becoming increasingly difficult. In addition, the remaining ashes after incineration generally carry relatively high concentration of heavy metals and toxicity (Wei et al., 2003). These require disposal through landfill to which, as highlighted earlier, regulatory measures impose increasing restrictions. Finally, incineration does not strictly support the waste management hierarchy whereby waste reduction, reuse and recycling are top priority (Defra, 2007a). Therefore, alternatives for disposal ought to be sought elsewhere.

In the North West region of England, United Utilities plc produces approximately 215, 000 tonnes per year (dry solids basis) of sewage sludge which are reduced to *c.*150, 000 tonnes per year after digestion (Whipp, 2007). The disposal strategy of the company is based upon a dual approach of recycling to farmland and incineration which are *c.*70% and *c.*30% respectively (Whipp, 2007). The disposal route to farmland appears to be the least expensive available option despite being performed at the water company’s cost with biosolids being provided free of charge and transportation, spreading and ploughing costs met by the sewage disposal industry in most circumstances. Cost-figures of the three main disposal options facilitated by United Utilities plc in 2007 indicated that agricultural recycling costs the company *c.*£150 per tonne of raw sludge (dry solids basis) compared to incineration (*c.*£250 per tonne of raw sludge – dry solids basis), and landfill (*c.*£200 per tonne of raw sludge – dry solids basis). The treatment and disposal of sewage sludge accounts for over 50% of United Utilities plc’s operating budget for the wastewater business in the North West region (Whipp, 2007). It is necessary to maintain, and where possible increase, current levels of biosolids recycling to farmland in order to avoid other expensive routes for disposal. The strategy of the company towards sludge management and disposal requires the development of sustainable sludge treatment processes and management practices. Improvement of biosolids quality will contribute to minimise environmental concerns (Davis, 2007) and secure the agricultural route.

1.2 The need for recycling biosolids to land

In Europe, it is widely accepted that recycling of organic materials, including biosolids, to agricultural land is the best practicable environmental option (Chambers and Rudd, 1995; Edge, 1999; Defra, 2007a). Recycling also contributes to complete the natural nutrient and carbon cycles (Taylor et al., 2009). Much evidence suggests that future supply of mineral fertilisers, such as N- and P-fertilisers, will be tight (Brentnall, 2008). Developments in the nitrogen fertiliser industry are driven by both feedstock availability and price (Brentnall, 2008).

In recent years, high feedstock prices combined with investments made in the energy sector; i.e. liquefied natural gas, have diverted resources, finance and equipment supply, restricting expansion in the nitrogen fertiliser industry and driving prices upwards (Brentnall, 2008). It is envisaged that the demand for nitrogen fertilisers will increase significantly in response to agricultural development, mainly in the developing world, and also as a result of the enforcement of legislation concerning biofuels in the EU (Brentnall, 2008). Hence, the supply-demand relationship is likely to remain unstable exerting pressure on the price of nitrogen fertilisers.

With particular regard to phosphorus, Evans (2009) highlighted that up to 95% of phosphorus can be recovered from wastewaters and concentrated into the sludge which, following adequate treatment, can be applied to agricultural land. Phosphorus is a scarce resource (Steén, 1998) and although there is no general consent (Gilbert, 2009; Hilton et al., 2010) some estimates suggest that global phosphate reserves may be depleted in approximately 50 to 100 years at present rates of extraction (Herring and Fantel, 1993; Johnston, 2008; Evans, 2009; Hilton et al., 2010). Furthermore, availability of high quality phosphate mineral reserves; e.g. those free/low cadmium or chlorine content and those identified as high grade ore ($\geq$30% P_2O_5), are limited resulting in such phosphates either being potentially un-saleable or restricting investment for exploitation (Brentnall, 2008). However, a recent report produced by IFDC (2010) suggested that there are *c.*60 billion metric tonnes of phosphate rock worldwide which, to some extent, discarded the idea of a peak phosphorus event in the short/medium terms. Instead, the report by IFDC (2010) provided evidence indicating that these reserves could sustain current production levels for the next 300 to 400 years.

Nevertheless, agriculture plays a key role as *c.*80% of the total phosphate extracted worldwide is used for mineral fertilisers (Steén, 1998; Evans, 2009). The expected increase in the global population needs to be accompanied by developments in agricultural production (Pandya-Lorch et al., 2001) to ensure food supply is not affected. Pandya-Lorch et al. (2001) based on IFPRI (1999)'s projections indicated that between 1995 and 2020 global demand for cereals would increase by *c.*40% and for meat *c.*60%. At national level, the challenges associated with food security, sustainability and health are being addressed through the recent launch of the Food Strategy 2030 (Cabinet Office, 2008). The required increase in agricultural production will bring about increased demand for mineral fertilisers (Isherwood, 2003), including phosphorus (Steén, 1998). Weikard and Seyhan (2009) highlighted that an important aspect of recycling is that it contributes to mitigate the demand for finite resources such as rock phosphate and to slow down the rate of depletion.

The need for recycling is also true for energy demanding nitrogen (Schröder and Bos, 2008). In fact, it is estimated that up to one-third of the energy used in intensive arable farming is required to produce the nitrogen fertilisers used (Cooke, 1975; Dawson, 2008). Through stable fertiliser demand and improved efficiency of nutrients management by means of recycling, the cost of food production may also be maintained (Weikard and Seyhan, 2009). The increase in the price of mineral fertilisers observed in recent years (Brentnall, 2008); e.g. *c*.30% and *c*.40% increase for ammonium nitrate and triple superphosphate respectively between 2005 and 2009 (Nix, 2006-10), lead an increasing number of farmers to looking towards organic materials to meet crop nutrient requirements and maintain the fertility status of their soils (Taylor et al., 2009). In practice, however, recycling of biosolids to farmland presents several difficulties such as land availability, mainly in the proximity of wastewater treatment works, and farming practice (Moseley, 1999), nutrients concentration, transport, storage, handling and spreading.

Although the benefits of applying biosolids to agricultural land have long been acknowledged (e.g. WRC, 1989; Epstein, 2003), the fertiliser potential of biosolids remains a major concern for most farmers. There are also concerns regarding heavy metals concentrations in biosolids and potential accumulation in the soil and subsequent transfer on to crops (Johnston, 2008). To certain extent, this has been controlled by limiting inputs at source and by regulating application rates (Evans, 2008). In this respect, maximum permissible concentrations of heavy metals in the soil are specified under the Sludge (Use in Agriculture) Regulations 1989 and the Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1990) to ensure the protection of the environment and the soil when sludges are used in agricultural production.

In addition, the relatively low N:P ratio of biosolids can result in build-up of soil phosphorus when biosolids application is performed to meet all or a large proportion of the crops nitrogen requirements (Edge, 1999). Research (Withers and Flynn, 2007) has shown that soil extractable phosphorus was found to increase with the rate of biosolids phosphorus applied. In the proximity of the wastewater treatment works, soil-P enrichment can have implications upon the costs of recycling since soils showing high soil-P indexes require less frequent biosolids applications. As a result, the recycling radius from wastewater treatment works needs to be expanded in order to meet the same disposal targets (Edge, 1999). In addition, the use of sludges in agriculture has been restricted as a result of their variable chemical composition (Sommers et al., 1976; Sommers, 1997).

A number of studies (Bowden and Hann, 1997; Cordovil, 2003; Cordovil et al., 2007) highlighted that the amount of nitrogen available following soil application of organic residues has not been clearly determined; therefore, there is a need to provide a better understanding of the nitrogen release characteristics of organic materials recycled to farmland. The nutrient release characteristics of biosolids are generally largely unquantified and the relatively poor understanding (Cordovil et al., 2007) can result in damage to the environment. All these factors combine to provide a highly variable agronomic performance which constrains the recycling through the agriculture route (Moseley, 1999). Johnston (2008) emphasised that the practice of recycling of organic materials must provide a benefit to agriculture with no long term effects on soil fertility and productivity, be acceptable to the public, financially viable, environmentally desirable and comply with legislative requirements which ought to have at least regional applicability.

1.3 Organomineral fertilisers (OMF)

A novel technique was proposed by United Utilities plc to produce organomineral fertilisers (OMF) using biosolids granules. This new product concept would appear to be a sustainable alternative for the recycling of biosolids to land and it could significantly contribute to overcome some of the problems highlighted earlier in **Sections 1.1** and **1.2**.

The production of OMF involves the use of digested sewage sludge cake (*c.*25% dry solids), urea (46% N) and potash (60% K_2O) as raw materials. Digested cake undergoes a granulation process which also increases the dry solids content to *c.*70%. Following this process, granules are further dried to achieve *c.*95% (dry solids content) and sieved for dust removal, and granules of up to 6 mm in diameter are subsequently selected for urea-coating. A more detailed description of the production process and the pilot granulator is provided in **Appendix A.1.1**. The core of the granules consists of the biosolids which contains a slower release nutrients fraction. This is covered with a thin layer of urea which provides a readily available nitrogen source. Potash is also added during the coating process together with urea which increases the content of potassium. The content of potassium in biosolids is normally very low (Gurjar, 2001); e.g. $\leq$0.2% (w w^{-1}), and it is usually insufficient to meet the requirements of most crops when they are applied at rates in line with standard farm practices. The technique was used to produce two OMF products: OMF_{15} and OMF_{10}. These have, approximately, the following NPK compositions: 15:4:4, and 10:4:4, respectively.

It is important to note that phosphorus was not added to the product and that the P-content in the OMF is equivalent to that existing in the biosolids. To some extent, it was possible to overcome the problem of low N:P ratio in biosolids and the general imbalance in their nutrients composition which, as highlighted earlier, can result in build-up of soil phosphorus. The addition of nitrogen to the product and the corresponding increase in the N:P ratio will better match the requirements of the land-bank for the recycling of biosolids given the relatively high soil-P indexes reported in the main operating area of United Utilities plc. Nitrogen concentrations in excess of 15% in the OMF are technically possible but this has implications upon the cost of OMF production and the potential amount of biosolids going through recycling. This nitrogen concentration in the product has been suggested (Le, 2006) to be a reasonable upper limit for OMF production, both technically and economically.

Such product development must ensure that modern agricultural requirements can be satisfied. For this, the chemical characteristics of the products have to be consistent and clearly quantified and their physical characteristics should allow application using standard fertiliser spreading equipment. It is envisaged that the development of OMF will go some way to secure the agricultural route for disposal by offering farmers a value added product. It may also enable farmers to reduce the reliance on mineral fertilisers which are going up in price. The potential environmental risk associated with the use of OMF and the effects on cereal crops and grass need to be quantified. Effective communication of technical-scientific information to end users is crucial to establishing public confidence in the use of organic-based fertilisers. Strategies for the application of OMF need to be developed to be able to optimise their agronomic performance and to minimise potential environmental risks arising from their use. It is understood that the development of OMF products constitutes a sustainable approach towards the efficient use of organic resources in agriculture. This can have a beneficial effect on the cost of production of food crops. Trott (2002) emphasised that the development of new products provides organisations with the opportunity for growing their businesses as new and improved technologies are usually recognised to be the drivers of competitive advantage (Rickard, 2006). The development of OMF represents a significant technological change to the way sewage sludge (biosolids) is currently being recycled to agriculture and it appears to be in line with current environmental and regulatory requirements.

Figure 1.1 summarises the various stages in the development of OMF and it shows the contribution of the EngD project towards it. The initial two stages required the product concept to undergo a qualitative screen followed by feasibility analyses. Effectively, the concept was analysed to determine its compatibility with the company’s objectives and resources.

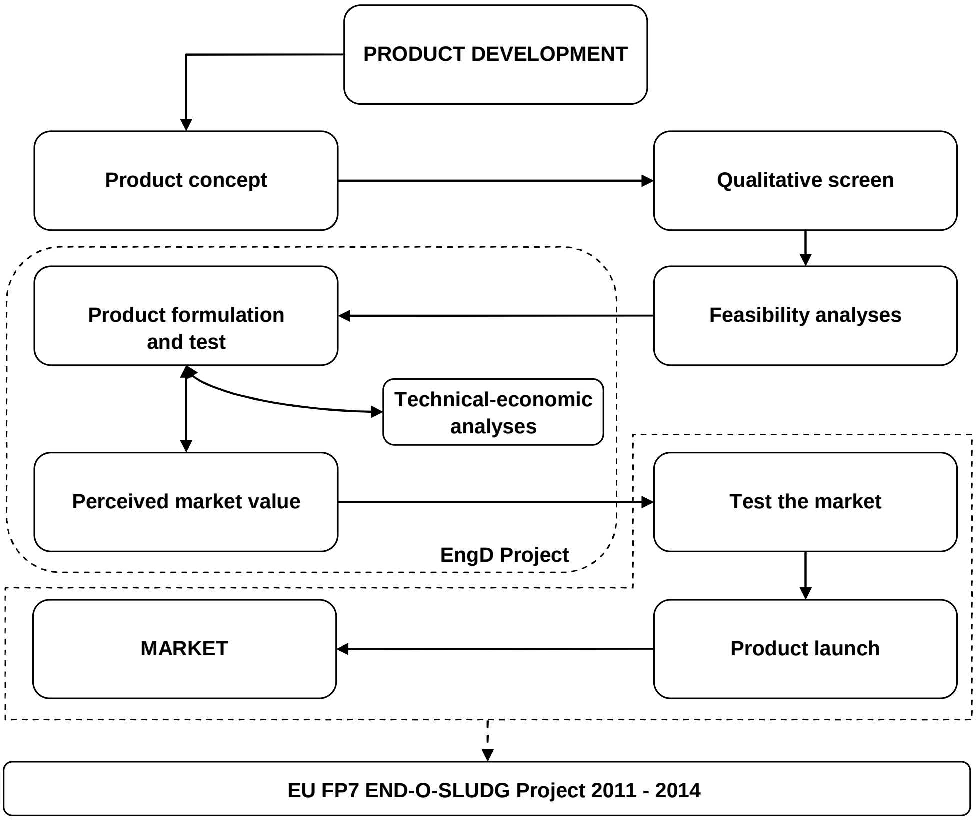


Figure 1.1: A chart summarising the stages in the development of OMF and the contribution of the EngD project (adapted from: McDonald & Christopher, 2003).

The EngD project contributed to this new product development by focusing upon the subsequent two stages which involved the specification of the products and their testing in the range of experiments conducted. These involved different experimental scales, including laboratory, glasshouse and field studies and the data derived from the experimental work allowed basic technical-economic analyses to be undertaken. Subsequently, and based upon earlier studies, a methodological approach was developed which aimed at determining the perceived market value of OMF which is a necessary step prior to testing the market. The successful completion of this latter stage will enable United Utilities plc to launch the product and to establish it competitively in the market. This work is to be conducted under the EU FP7 END-O-SLUDG Project 2011-2014 which aims at producing marketable sludge derivatives from sustainable processing of wastewater in a highly integrated treatment plant. The FP7 Project involves 14 partners from 5 countries, including industry, academia and the public sector with a budget of €5.5 million (Le, 2011).

Through the EngD project, the regulatory, environmental, agronomic, engineering, and technical-economic aspects of the use of organomineral fertilisers in cereal crops and grass will be investigated to provide sound understanding on OMF management. The following sections provide an overview of the research conducted which includes the overall aim and objectives, an outline of the methodological approach and a description of the thesis structure.

1.4 Project description

1.4.1 Research aim

The aim of this research is to determine the effects in cereal and grass crops of using organomineral fertilisers (OMF) made from nutrients-enriched biosolids granules and to contribute towards the understanding of nutrients management and dynamics in agricultural systems with particular regards to nitrogen and phosphorus.

1.4.2 Objectives

To achieve the overall aim of the research the following objectives were defined:

1. To develop the chemical and physical specifications for a range of OMF products which include: suitable product formulations and physical characteristics for application in winter wheat (*Triticum aestivum L.*) and rye grass (*Lolium perenne L.*).
2. To determine the fertiliser potential and quantify the nutrient release characteristics of formulated OMF products with a view to recommending the optimum application rates on the crops mentioned above.
3. To determine the potential environmental risks associated with the use of OMF products with particular regards to nitrogen and phosphorus leaching and denitrification via N_2O.
4. To conduct technical-economic analyses to determine the feasibility of using OMF in cereal crop production and to develop a protocol for estimating the perceived market value of OMF products based on the use of contingent valuation techniques.
5. To provide practical recommendations.

1.5 Outline methodology

In order to meet progressively the aim and the objectives outlined above, the research was sub-divided into four stages (**Sections 1.5.1** to **1.5.4**). Each of these stages partially contributed to achieve the objectives and the overall aim of the research. The statistical analyses of the experimental data were undertaken using GenStat Release 10.1 (2007). Laboratory analyses were conducted in accordance with the protocols and standards adopted by Soil and Water Laboratory at Cranfield University.

1.5.1 Stage I

Stage I consisted of developing an understanding of the research and the current situation in relation to sewage sludge (biosolids) management and disposal. The need for the water industry to find a sustainable solution and to secure the agricultural route for disposal was analysed. For this, a literature review was required which also allowed the overall aim and objectives of the research to be drawn. The literature review was later extended to provide an understanding of nutrients management and dynamics in agricultural systems, and to aid establishing the experimental designs in **Stages II** and **III** of this research. The second part of the literature review focused upon the use of nitrogen and phosphorus in crop production. The following aspects were considered in **Stage I**:

- Identification of cropping and grassland areas in Great Britain,
- Identification of soil types and their use in the North West of England which is the main operating region of United Utilities plc,
- Brief analysis of the fertiliser market and an overview of the fertiliser products commonly used in cereal crops and grass,
- Review of the legislation in force concerning the agricultural use of sewage sludge (biosolids) and organic materials as well as mineral fertilisers,
- Understanding the environmental risks associated with the use of sewage sludge (biosolids) and mineral fertilisers in agriculture and the issues regarding the public perception and acceptability of biosolids across the farming community.

Following this preliminary work, it was possible to engineer the chemical composition and the physical characteristics of two organomineral fertilisers (OMF) for application in winter wheat and rye grass. As a result, objective number one of this research, as outlined in **Section 1.4.2**, was achieved and two OMF products with different nitrogen concentrations were suggested: OMF_{10} and OMF_{15}. As highlighted earlier, these have the following NPK compositions: 15:4:4 and 10:4:4. The specification of the products and the rationale for the proposed formulations are provided in full in **Chapter 3**. The proposed formulations took account of the following:

- NPK composition of base biosolids granules,
- Nitrogen application rates in winter wheat and grass,
- Phosphorus and potassium application rates in winter wheat and grass in relation to soil P- and K-indexes, and

- Technical guidance provided by United Utilities plc regarding maximum nitrogen concentrations in the OMF.

The phosphorus content in the OMF is equivalent to that of the base biosolids granules as phosphorus is not added to the product. The addition of urea-nitrogen through coating of the granule increases the N:P ratio in the biosolids and it allows correcting imbalances in their nutrients composition. It is expected that this will contribute to reduce the risk of soil phosphorus build up that has been observed with the continuous use of biosolids; especially, when these are applied on the basis of plant available nitrogen. The study of the physical properties of OMF included the following determinations:

- Particle size analysis and size distribution,
- Bulk density,
- Particle density, and
- Particle strength.

Based on earlier work (Hofstee, 1993; Miller and Parkin, 2005; Parkin et al., 2005; Farnish and Bradley, 2007), it can be stated that these physical properties are of high importance as they are likely to influence the spreading characteristics of the fertiliser, and also their segregation and fracture during handling and spreading. In addition, these properties give an indication of the materials' requirements for storage and transport. Particle density and particle diameter were needed to feed the particle trajectory model which is reported in **Chapter 4**. The spreading characteristics of the product were tested in-field conditions using a pneumatic fertiliser spreader (Kuhn 2212) and the distribution uniformity across the working width of the applicator was determined and recorded following the specifications outlined in ASAE (1999). The study of the chemical characteristics of OMF included the following determinations:

- Total nitrogen,
- Total phosphorus,
- Total potassium.

In addition, cadmium (Cd), copper (Cu), and zinc (Zn) were determined in the biosolids and the two OMF for the fertiliser batch used in the harvest season of 2006-07. This was performed to have an indication of the levels of specific heavy metals likely to be encountered in the fertilisers. Cadmium is not an essential element for plant growth and may be toxic at low concentrations (Molloy et al., 2005).

It is also linked to a number of human diseases and can be transferred from the soil to the food chain (Singh, 1991) through translocation to the grains in cereal crops (Johnston and Jones, 1995). Copper and zinc, despite being essential elements, can be toxic to plants and soil microorganisms at high concentrations in the soil (Molloy et al., 2005). Maximum permissible levels of heavy metals in soil must be observed when biosolids are used in agriculture and guidance levels can be found in the Soil Code (MAFF, 1998b).

1.5.2 Stage II

Stage II consisted of developing the methodology and conducting the experimental work in relation to objective number two of the research as outlined in **Section 1.4.2**. The following work was undertaken in at this stage:

- Investigation into the nutrient release characteristics of OMF_{15} with particular regards to nitrogen and phosphorus in comparison with urea (46% N) and single superphosphate respectively (47% P_2O_5), and
- Investigation into the fertiliser potential of OMF_{15} and OMF_{10} for application in winter wheat and rye grass in comparison with base biosolids granules and urea.

The study of the fertiliser potential of OMF was done in two sets of experiments as follow:

- Field studies (College Farm, Silsoe) using winter wheat and rye grass grown in small plots on a sandy loam soil. The experiments were conducted as follow to allow for the crop rotation to be continued:
  - 1st and 2nd winter wheat in Avenue Field during the harvest seasons of 2006-07 and 2007-08 respectively followed by two years (2009 and 2010) of perennial rye grass established in March 2009; and
  - 1st and 2nd winter wheat in Chippies Field during the harvest seasons of 2008-09 and 2009-10 respectively.
- Glasshouse studies (Cranfield University) over a three years period (2007-09) using rye grass established in April 2007 and grown in pots under semi-controlled environmental conditions. The experiment used two soil types both collected from the College Farm at Silsoe; a sandy loam from Avenue Field, and a clay loam from Showground Field.

In the field studies, the fertiliser potential of the products was determined through measuring the responses of the crops to increasing nitrogen application rates. These included determination of grain yield in winter wheat and dry matter yield in rye grass.

Nitrogen was applied to both crops in the range of zero (control) to 250 kg [N] ha^{-1} at regular increments of 50 kg [N] ha^{-1}. In addition, the maximum and the optimum nitrogen application rates and their corresponding crop yields were estimated for winter wheat and rye grass following the methods described in James and Godwin (2003), and Morrison et al. (1980) respectively. In addition to grain yield, the following crop parameters were measured in winter wheat:

- Total above the ground biomass,
- Harvest index,
- Weight of 1000 grains,
- Total nitrogen in grain (harvest of 2006-07 and 2007-08).

The following soil chemical properties were measured in the field:

- Total soil nitrogen
- Soil mineral nitrogen,
- Soil extractable phosphorus,
- Soil organic matter,
- Soil pH,
- Soil extractable potassium, and
- Heavy metals: cadmium (Cd), copper (Cu), zinc (Zn), and lead (Pb).

Measurements were conducted routinely. This allowed making comparisons between the treatments and the unfertilised control and also to determine changes occurred in the selected soil properties overtime as a result of the continuous application of biosolids, OMF and urea to the soil. Plots were allowed to receive the same fertiliser treatment year on year to examine the build up and residual effects of soil nutrients. In order to do this, the experimental site was surveyed which permitted re-locating the plots in the same place in subsequent years once tillage operations and drilling were completed.

In the glasshouse studies, in addition to the unfertilised control soils, nitrogen was applied to grass at two rates 150 and 300 kg [N] ha^{-1}. The same soil parameters as those listed before in the field studies were also determined in the pots. The crop responses to applied nitrogen were measured through the production of dry matter. A total of three cuts were performed annually throughout the growing season both in the field and glasshouse studies; except for the grass in Avenue Field which had only two cuts in 2010.

Nitrogen content in harvested plant material was determined to quantify nitrogen uptake by the crop. However, and in order to reduce the amount of analyses, this determination was only done for the grass grown in the glasshouse.

The study of the nutrients availability from applied OMF was conducted in a series of incubation experiments in the Soil Laboratory (Cranfield University) under controlled conditions of temperature and soil moisture content over a period of 90 days (OECD, 2002). The experiment used the same soil types as those described for the studies in the glasshouse which included a sandy loam and a clay loam soil, both from the College Farm at Silsoe. Due to the enhanced fertiliser potential of OMF_{15} compared with OMF_{10}, a decision was made to use only this OMF product for the laboratory studies. The use of only one type of OMF also helped to maintain the experiment within a manageable size. The release of nitrogen and phosphorus from OMF_{15}-treated soils was compared to the control (zero fertiliser) soil and soil treated with urea and single super-phosphate respectively. Nitrogen and phosphorus application rates were equivalent to 150 and 300 kg [N] ha^{-1}, and 150 and 300 kg [P_2O_5] ha^{-1} respectively. In addition, soil samples were taken every 30 days for analysis of soil mineral nitrogen in the controls, OMF_{15} and urea amended soil; and for analysis of soil extractable phosphorus in the controls, OMF_{15} and single superphosphate treated soils respectively.

1.5.3 Stage III

Stage III consisted of developing the methodology and conducting the experimental work in relation to objective number three of the research as outlined in **Section 1.4.2**. This work required the construction of a lysimeters station which was built at Sand Pit Field (College Farm, Silsoe) in February 2008. The design and drawings of this facility as well as a photographic record of the work conducted are shown in **Appendix A.1.2** and **A.1.3.** The experimental site comprises 25 lysimeters which are buried in the soil and have the following dimensions: 575 mm in diameter and 1000 mm depth.

The lysimeters studies are still ongoing work. Time did not permit reporting in full the data collected over the two years experiments. However, the experimental work has been completed as of August 2010 and a recommendation (**Chapter 11**) has been made to the author of this thesis to analyse the data and report it in an appropriate journal as advised by the supervisors. Preliminary findings of this work were presented in the following conferences and the papers have been attached to this document in **Appendix A.1.4** and **A.1.5**.

- Antille, D.L., Sakrabani, R., and Godwin, R.J., 2008. Methodological approach to identifying the properties of a novel organomineral fertiliser – Part II: environmental aspects and OMF application. Cranfield Multi-Strand Conference: Creating wealth through research and innovation [Paper No.: 133]. Cranfield University, MK43 0AL, UK. 6-7 May 2008.

- Antille, D.L., Sakrabani, R., and Godwin, R.J., 2009. Nitrogen budget following application of nutrient enriched biosolids to agricultural land: a lysimeters case study. In: Grignani, C., Acutis, M., Zavattaro, L., Bechini, L., Bertora, C., Gallina, P.M., and Sacco, D., 2009 (Eds). Proceedings of the 16th Nitrogen Workshop: Connecting Different Scales of Nitrogen Use in Agriculture. University of Turin, Italy, 28 June – 01 July 2009. [Paper No.: P153].

The data collected from the lysimeters will be used to provide estimates of N_2O emissions, and nitrogen and phosphorus leaching following application of OMF and urea to wheat and rye grass. The lysimeters were filled with a sandy loam soil which has the following (approximately) particle size analysis: 60% sand, 28% silt and 12% clay. The soil was selected to have a similar textural analysis to that of Avenue and Chippies Fields respectively so that to provide a link between both studies. Twelve lysimeters were used with perennial rye grass (established in April 2008) and twelve with wheat, as follow: spring wheat 2008 (1st wheat), winter wheat 2008-09 and 2009-10 (2nd and 3rd wheat respectively). The crops were applied annually with the equivalent to 250 kg [N] ha^{-1} using urea, OMF_{15} and a 1:4 mixture of urea-N and OMF_{15}-N. For both crops, the total nitrogen application rate was split into two dressing equivalent to 125 kg [N] ha^{-1} each. The nitrogen application rates used were in line with those reported in earlier studies on N_2O emissions involving application of biosolids to agricultural land (e.g. Thorman et al., 2009). Leachate was regularly collected for determination of total oxides of nitrogen (TON) and phosphates in water and the volume of leachate was measured and recorded. The following measurements were conducted on the crops:

- Wheat:
  - Grain yield,
  - Total above the ground biomass,
  - Harvest index,
  - Weight of 1000 grains, and
  - Nitrogen content in grain.

- Grass:
    - Dry matter yield, and
    - Nitrogen content in harvested plant material.

For grass, a total of three cuts were performed annually throughout the growing season. In addition, the following determinations in the soil were conducted annually for all lysimeters prior to the first application of fertiliser, and in post-harvest of the wheat crop or after the third cut in grass:

- Total soil nitrogen,
- Soil mineral nitrogen
- Total soil phosphorus,
- Soil extractable phosphorus.

Due to the cost of the analysis, measurements of N_2O emissions were limited to lysimeters occupied with wheat only. In order to account for temporal variability in N_2O emissions and to comply with the IPCC specifications (IPCC, 1997a-b & 2006) measurements were conducted over a period of 24 months. These were performed using the static chamber technique as described in Thorman et al. (2007); although larger chambers (dimensions 630 x 630 x 250 mm) were required and these were especially designed to fit on top of the lysimeters (**Figures 1.2** and **1.3**). The concentration of N_2O in the samples was measured by gas chromatography and the N_2O increase over the enclosure time was subsequently used to estimate the N_2O emission rate. Background concentration of N_2O in the air was also measured. Fluxes were measured daily for a period of three days following the application of fertiliser and every two weeks thereafter.
A copy of the protocol facilitated by ADAS Boxworth is attached in **Appendix A.1.6**. During the winter time (November to February) the sampling frequency was reduced to one event per month. Soil temperature and soil moisture content were recorded throughout the experiment.

The **total cost** for the construction of the lysimeters station in Sand Pit Field was **£1252** including VAT. This sum includes the cost of 2 concrete rings of dimensions 1800 x 1000 mm and 1800 x 500 mm respectively, pipes and fittings required to connect barrels with the leachate collectors, a digger and a driver for 2 days, and the materials needed to manufacture a clip to allow the lifting of the rings and the barrels with a forklift. In addition, 8 tonnes of soil were purchased from a local supplier at a cost of **£585** including VAT and delivery to Silsoe Campus.

Figure 1.2: A picture showing the chambers used at the lysimeters station for measurement of N_2O emissions.

Figure 1.3: Overview of lysimeters station with the established crops and N_2O measurements being conducted.

1.5.4 Stage IV

Stage IV consisted of developing the methodology in relation to objectives number four and five of the research as outlined in **Section 1.4.2**. The results from the experimental work conducted in **Stage II** and the management and business aspects of this research were brought together at this stage as follow:

- The experimental data which included the agronomic, environmental and technical-economic aspects of the work was integrated and discussed,
- From the above, recommendations for the use of OMF were made. These were based on the findings of the experimental work conducted which support the good use of OMF in wheat and grass. Recommendations were made for both United Utilities plc and farmers,

- The methodology proposed for the investigation of the willingness to pay for OMF was presented based on earlier studies (Pegurara-Gasparin, 2009),
- The main findings coming from this research were summarised and the overall conclusions were drawn. Recommendations for future research in this field were also made.

In addition to the above, and in relation to the need to investigate the farmers' acceptance of OMF, a pilot choice experiment was conducted. The methodological approach and the results obtained along with the difficulties encountered in applying this technique were reported in **Chapter 8**. It was initially considered that this technique would be appropriate to derive willingness to pay estimates of OMF. Choice experiments are commonly used to determine the characteristics or attributes of a product that customers prefer most and therefore are willing to pay for (Travisi and Nijkamp, 2008). It allows identifying the elements that influence customers' decision when purchasing a particular good or service. For this, a simple questionnaire was first drawn and distributed amongst 12 respondents who were asked to choose between two fertiliser types given three attributes of the products; these included the nitrogen content and the price of the fertiliser.

This preliminary investigation did not report satisfactory results and it required re-designing the questionnaire drawn in the first instance to include a fourth attribute. However, the revised version of the questionnaire was complex to answer and it was reflected in the poor number of responses returned. As a result, the required statistical analyses could not be undertaken and the work did not progress. It was therefore decided to revise the methodological approach and to use contingent valuation techniques instead. The methodology presented in **Chapter 8** follows the work reported in earlier studies (Pegurara-Gasparin, 2009) which investigated the acceptance of on-farm automated traceability systems (Peets, 2009).

1.6 Statistical analyses

The statistical analysis of experimental data was undertaken using GenStat Release 10.1 (2007) and involved the analysis of variance (ANOVA), the least significant differences to compare the means (LSD, 5% level), and both linear and non-linear regression analyses. A probability level of 5% ($p<0.05$) was used.

1.7 Thesis structure

A summary of the methodological approach and the thesis structure is shown in **Figure 1.4**.

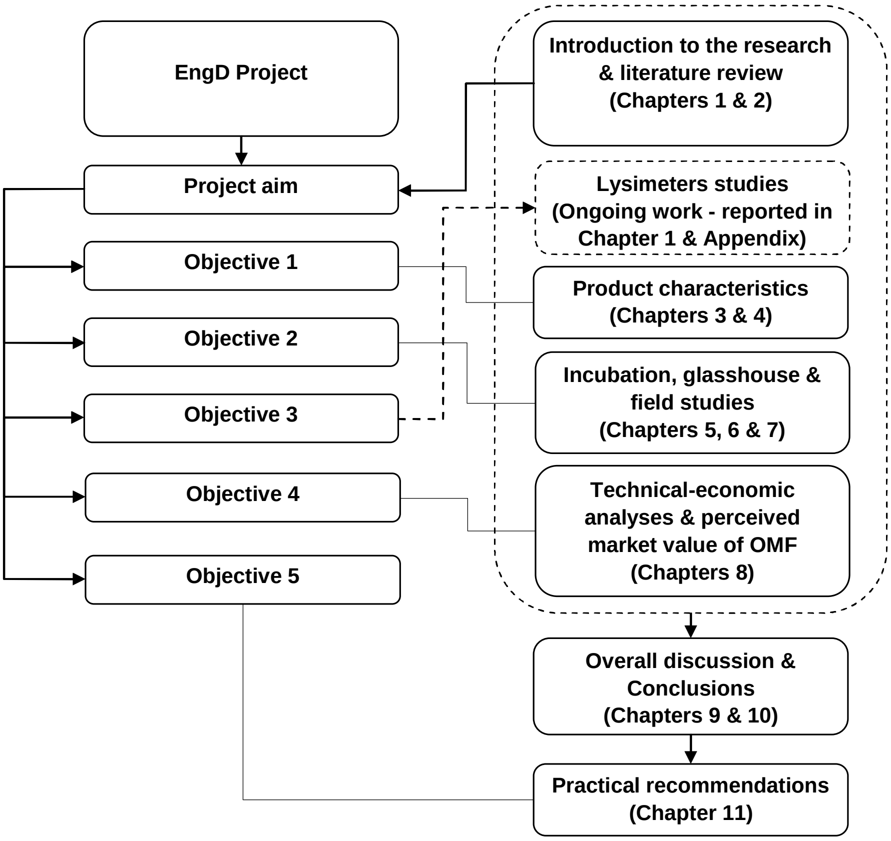


Figure 1.4: Outline of the research methodology and summary of the thesis structure.

Following this introduction to the research, a literature review is presented in **Chapter 2** which focuses upon the recycling of biosolids to agricultural land and the nutrient dynamics in agricultural systems with especial regards to nitrogen and phosphorus. It addition, it discusses the various sewage sludge disposal options and it examines the relevant legislation in force as one of the main drivers relating to sludge management and disposal. The methodology used in each of the experiments is presented separately in their corresponding chapters (**Chapters 3-8**). The experimental work always used mineral fertilisers and where appropriate, biosolids granules, as a base for comparison with OMF. This was partially due to the nature of the OMF products which are made of biosolids granules and urea-N and potash. In addition, there was a need to compare OMF against consistent fertiliser sources with regards to the chemical composition and physical characteristics; aspects that are commonly achieved with inorganic fertilisers but that can be more difficult with organic materials such as compost or FYM.

In **Chapter 9**, an attempt was made to analyse the data integrally and to discuss the main findings coming from the individual experiments. This enabled drawing the overall conclusions of this research (**Chapter 10**) and providing practical recommendations (**Chapter 11**) concerning the use of OMF in the crops investigated.

In addition to the conference papers mentioned earlier, which reported preliminary findings of the work on lysimeters, the following publications were produced and presented:

- Antille, D.L., Sakrabani, R., Tyrrel, S.F., and Godwin, R.J., 2009. Organomineral fertilisers: nutrient dynamics and agronomic characteristics. Proceedings of 14th European Biosolids and Organic Resources Conference, Workshop and Exhibition. Aqua-Enviro Technology Transfer, The Royal Armouries, Leeds, UK. 9-11 November 2009. [Paper No.: 04].
- Antille, D.L., Sakrabani, R., and Godwin, R.J., 2009. Organomineral fertilisers: nutrient dynamics and evaluation of agronomic characteristics. Proceedings of the American Society of Agricultural and Biological Engineers (ASABE). [Paper No.: 095981]. St. Joseph, MI (49085-9659) 21-24 June 2009.
- Antille, D.L., Sakrabani, R., and Godwin, R.J., 2008. Organomineral fertilisers: nitrogen dynamics and evaluation of agronomic characteristics. Proceedings of the American Society of Agricultural and Biological Engineers (ASABE). [Paper No.: 084000]. St. Joseph, MI (49085-9659) 29 June-02 July 2008.
- Antille, D.L., Sakrabani, R., and Godwin, R.J., 2008. Evaluation of crop responses to organomineral fertilisers and measurement of nitrogen availability in controlled laboratory conditions. [Paper No.: 2008-A-1207]. EuroSoil 2008, Technical University of Vienna, Austria, 25-29 August 2008.
- Antille, D.L., Sakrabani, R., and Godwin, R.J., 2008. Methodological approach to identifying the properties of a novel organomineral fertiliser – Part I: agronomic aspects. Cranfield Multi-Strand Conference: Creating wealth through research and innovation [Paper No.: 124]. Cranfield University, MK43 0AL, UK. 6-7 May 2008.
- Antille, D.L., Gedara, S., Le, M.S., Tyrrel, S., Sakrabani, R., and Godwin, R.J., 2008. Organomineral fertilisers for sustainable sludge recycling. Proceedings of The Chartered Institution of Water and Environmental Management. CIWEM 6th North Wales Wastewater Treatment Conference – Part II: Sludge Management. Warrington, UK. 21 February 2008.

CHAPTER 2

LITERATURE REVIEW

2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews existing available knowledge on sewage sludge (biosolids) recycling to farmland. The first part of this literature review examines the current land use in Great Britain, the fertiliser market, the issues faced by the water industry in relation to biosolids recycling to farmland, and the need to secure the agricultural route for disposal of sewage sludge. Alternative routes for disposal of sewage sludge are also discussed and pertinent legislation in force is reviewed. The second part of the chapter (**Section 2.6**) focuses upon the nutrient dynamics in agricultural systems with particular regards to nitrogen, their effects on crop production and the potential environmental impacts associated with their use in agriculture. Phosphorus is briefly examined to aid in the interpretation of some of the results coming from the experiments which will be discussed in later chapters.

2.2 Arable and grassland areas in Great Britain

2.2.1 Overview

The information presented in this section is based on Defra (2009a) which reported that for the harvest season of 2008 there were approximately 11 million hectares of managed agricultural land in Great Britain; 42% of this land was occupied by tillage cropping (4.7 million hectares) and the remaining 58% (6.4 million hectares) were grassland. It was also indicated that 84% of the total grassland area was permanent being five years old or older. **Figure 2.1** illustrates the area occupied individually by major crops in Great Britain in 2008.

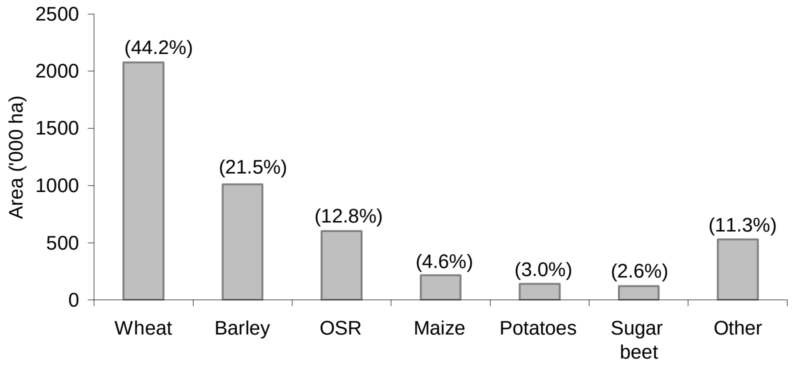


Figure 2.1: Area ('000) occupied by main crops in Great Britain for the harvest season of 2008 and the percentages with respect to the total tillage area. OSR: oilseed rape. Other (crops) includes linseed, peas, beans, and vegetables crops [Source: Defra (2009a)].

The total tillage area remained relatively constant for the period 1997-2008 despite some changes observed in some cropping areas. Breaking down the information shown in **Figure 2.1**, spring and winter barley occupied 12.7% and 8.8% of the total tillage area respectively whereas spring and winter oilseed rape represented 10.8% and 2% respectively (Defra, 2009a). In England, the total area on agricultural holdings in 2009 was approximately 9.5 million hectares of which 4.9 million hectares (52%) were occupied by crops (including bare fallow and temporary grass) (Defra 2009b). The remaining 48% of the land was mostly permanent grassland (Defra 2009b). As shown for Great Britain, wheat was the most widespread crop in England with an area estimated at 1.7 million hectares equivalent to *c*.65% of the total cereal area for 2009 (Defra, 2009b).

2.2.2 Soils and their use in the North West of England

This area is of particular interest for the project as it corresponds with the main operating region of United Utilities plc. A comprehensive description of the soils in the NW of England can be found from the Soil Survey of England and Wales (SSEW, 1983) and Ragg et al. (1984). According to this information, the following soil associations, in decreasing order of dominance, were identified in the surrounding area of Warrington (Lancashire, UK):

$$Salop\ \ 711m >>>> Blackwood\ \ 821b >>> Conway\ \ 811b >> Turbary\ \ Moor \geq Milford\ \ 541a$$

Salop (711m) is the dominant soil association in the area of Warrington and their soils were described by SSEW (1983) as: ‘fine loamy and clayey soils associated with fine loamy over clay’. A soil map and a brief description of the soil associations encountered near Warrington are provided in **Appendix 2.1.** Ragg et al. (1984) indicated that the soils in the NW of England were predominantly grassland (84%) and that more than 50% of this area corresponded to permanent grassland. In addition, cereal crops and oilseed rape occupied *c*.10% and *c*.1% respectively with most of the arable crops being sown in the autumn. A recent survey conducted by Defra (2008) showed very similar figures. Research (Skinner et al., 1992) showed that the fertility status of the soils in England and Wales experienced small changes during the period 1978-88. Their findings indicated that 20% of arable and 4% of grassland soils were found to have soil-P index 4 or higher. In addition, up to 45% of arable and 70% of grassland fields had soil-P index 2 or lower whereas for K 80% of arable and 89% of grassland fields were found to have index 2 or lower. In general, and using the soil indexes proposed by MAFF (2000), application of phosphate and potash to cereal crops and grass can be avoided when P- or K-indexes are respectively 3 or higher.

In the long term, however, omission of P and K fertilisation can result in significant yield losses as demonstrated by the long term experiments conducted at Rothamsted Research (Johnston et al., 2001a). When the amounts of P and K in the soil are below the critical levels for the soil-crop system, the efficiency of nitrogen use is significantly affected (Johnston et al., 2001b). This, in turn, may lead to negative effects on both the environment and the profitability of the farm (Johnston et al., 2001b). As highlighted earlier, a relatively large proportion of the soils across England and Wales are likely to have nutrient deficiencies suggesting that adequate fertilisation is needed to sustain crop yields.

The study conducted by Skinner et al. (1992) also showed that, at regional level and during the period 1983-88, in Northern England, Yorkshire-Lancashire, and East and West Midlands, the percentages of soils with P index 3 or above were 23%, 47%, 48%, and 51% respectively. The proportion of soils encountered at index 3 for K was 5% for Northern England and Yorkshire-Lancashire, and 29% and 15% for East and West Midlands respectively. A decline in the level of K in the soil was observed for Yorkshire-Lancashire during the same period (Skinner et al. 1992).

A later study conducted by Skinner and Todd (1998) also investigated the nutrients status of the soils in England and Wales for a period of 25 years (1969-93). This indicated that, on average, soil extractable P had declined in arable systems, although values remained at index 3 (26-45 mg [P] l^{-1}). In addition, for grassland, there was also a small decline in phosphorus levels at the end of the period; it was found to be in the upper portion of index 2 in 1993. The same study indicated that for ley-arable, soils were at P-index 3 by 1993. Soil extractable K did not show significant changes at the end of the period studied compared to the initial levels in the soil. With particular regards to the Northern region, this investigation demonstrated that soil K levels had decreased markedly and that up to 20% of the soils had K index 0 (Skinner and Todd, 1998). The overall decline in the levels of P and K in the soil appears to be consistent with the decrease in the use of phosphorus and potash fertilisers over the same period of time (FMA, 1993 & 1996; Skinner and Todd, 1998).

The decline of extractable P levels in grassland soils was also attributed to the decrease in the use of basic slag which is rich in P (Skinner and Todd, 1998). If this trend was to continue in the long term, it would provide an opportunity for the water industry to meet increasing disposal targets of sewage sludge (biosolids) through the agricultural route especially with regards to biosolids phosphorus.

2.2.3 Fertiliser use on arable crops and grassland

Table 2.1 shows the overall application rates of fertilisers in Great Britain for the period 2004-08 (Defra, 2009a) and more complete information can also be obtained from Chalmers (2001), and Pullinger and Yates (2006). The type of nitrogen fertiliser used in arable crops differs from that of grassland (**Table 2.1**). In arable cropping, more than 85% of the nitrogen comes from straight nitrogen sources whereas in grassland a larger proportion of the nitrogen is applied as compound nitrogen fertilisers. Overall, application rates of primary nutrients have shown some decline in recent years particularly in grasslands (Defra, 2009a; Fisher and Jewkes, 2009). This is probably the result of economic and regulatory influences on the structure of livestock farming combined with an improvement in the use of nutrients from organic sources (Pullinger and Yates, 2006; Fisher and Jewkes, 2009). The increase in the price of phosphate fertilisers observed in the past few years (Nix, 2008) had a significant effect upon phosphate fertiliser usage.

Table 2.1: Overall application rates of fertiliser (kg ha^{-1}) in Great Britain for the period 2004-08 [Source: Defra (2009a)]. Note: straight N fertiliser refers to a product containing only N; compound N fertiliser is a product obtained chemically by blending two or more primary nutrients (Richards, 2002).

	Fertiliser application rate (kg ha^{-1})				
Arable	**2004**	**2005**	**2006**	**2007**	**2008**
Total nitrogen	152	150	147	148	140
Straight N	132	129	128	133	125
Compound N	20	20	19	15	15
Total phosphate (P_2O_5)	41	40	35	34	31
Total potash (K_2O)	55	53	49	47	43
Grass	-	-	-	-	-
Total nitrogen	77	74	72	65	55
Straight N	27	28	28	26	23
Compound N	50	47	44	39	32
Total phosphate (P_2O_5)	17	16	16	14	10
Total potash (K_2O)	22	20	21	18	13

2.2.4 Fertiliser use on major arable crops and grassland

Fertiliser recommendations for individual crops are given in detail in MAFF (2000). **Table 2.2** shows the fertiliser use for the period 2004-08 for the main cereal crops grown in Great Britain and oilseed rape. In most circumstances, nitrogen is applied to winter wheat, winter barley, and oilseed rape using straight nitrogen fertilisers whereas for spring barley both straight and compound nitrogen sources are used. The choice of nitrogen fertiliser depends on agronomic factors and the soil conditions, particularly, the fertility status. Also, close periods for the application of nitrogen within NVZ restrict the use of nitrogen fertilisers during the winter time for autumn sown crops. Phosphorus is usually applied at or before drilling in the autumn as the seedling stage is the most prone to deficiency. Similarly, potassium is applied to the seedbed in arable crops but spring application is also an alternative for winter crops. Nitrogen is applied in the early spring using a straight nitrogen source but relatively low amounts of nitrogen may be applied to winter oilseed rape in early autumn. Depending on the total amount of nitrogen required by the crop, this may be split into two or more applications in the spring for arable crops, and spring and early summer for grass.

Table 2.2: Total nitrogen (N), phosphate (P_2O_5), and potash (K_2O) application rates given in (kg ha^{-1}) for wheat, barley, and oilseed rape in Great Britain for the period 2004-08 [Source: Defra (2009a)].

Year	Winter wheat			Winter barley			Spring barley			Oilseed rape		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
2004	197	39	48	144	46	62	104	44	57	202	39	46
2005	195	37	44	142	42	57	102	40	52	201	40	42
2006	192	34	41	136	37	54	101	39	60	191	34	38
2007	190	31	39	136	35	59	98	36	49	189	30	38
2008	178	27	36	134	35	51	94	34	47	191	29	36

Nitrogen requirements for winter wheat are very dependent on the intended market end use. Milling varieties are often cultivated as second wheat and they may be supplied with extra nitrogen (up to 20% more nitrogen than non-milling varieties) in order to achieve the 13% grain protein required (ADAS, 2010). Similarly, malting barley requires lower amounts of nitrogen compared with non-malting varieties due to the effect of the excess nitrogen in grain on the quality of malt. Oilseed rape production is forecasted to increase as it is a valuable source for biofuels production (FAO, 2005). This could bring about an increased demand for fertilisers for this crop.

However, this has not been observed in the past few years (**Table 2.2**) and there is, on the contrary, a downwards trend in the amount of fertiliser applied to this crop year on year. The existence of some restrictions upon oilseed rape production (IENICA, 2005) could limit the expansion of the crop and consequently the demand for fertilisers; e.g.: financial penalties may be imposed if the total area under oilseed rape exceeds certain limits. **Table 2.3** shows the fertiliser use for the period 2004-08 for grass in Great Britain for three different grass uses.

Table 2.3: Total nitrogen (N), phosphate (P_2O_5), and potash (K_2O) application rates given in (kg ha^{-1}) for different grass uses in Great Britain for the period 2004-08 [Source: Defra (2009a)].

Year	Silage			Grazing			Hay		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
2004	121	26	42	75	17	21	61	14	18
2005	124	25	40	74	16	19	52	14	17
2006	113	24	38	72	15	20	53	15	16
2007	106	21	33	63	13	17	47	11	15
2008	96	18	28	52	9	12	40	7	8

Fertiliser requirements for grass vary according to the type of livestock enterprise, intensity of production system and associated cutting and grazing regimes. The application of nitrogen to grasslands also depends on the soil nitrogen supply and whether clover is present in the sward. As for arable crops, recommendations for phosphorus and potassium are given according to the grass use and the soil index for P and K. In general terms, grass for silage requires higher level of nitrogen fertilisation compared with grazing and hay. Specific recommendations of fertiliser application rates are given in RB209 (Defra, 2000).

2.3 Mineral fertilisers used in the UK

2.3.1 Fertiliser suppliers in the UK

The main suppliers of mineral fertilisers in the UK are:

- **Yara:** straight nitrogen fertilisers and some blended and compound fertilisers;
- **Kemira/Grow-How:** ammonium nitrate and granular compound fertilisers;
- **Cleveland Potash:** mining and processing of potash and salts for use in fertiliser products.
- **Carrs Fertilisers:** liquid- and granular-N, broad range of compound fertiliser products.

Phosphorus is imported to the UK mostly from North Africa in the form of phosphate rock for conversion to phosphoric acid. Mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP) are imported from North America. The world supply of potash is very concentrated and only 12 countries are responsible for most of the production. Canada and the former Soviet Union countries account for approximately two thirds of the global production (Bain and Smith, 2007). In the UK, potash is mined from under the North Sea with an annual production of *c*.0.5 million tonnes of K_2O (Bain and Smith, 2007). Often, fertiliser products are tailored to meet particular nutritional requirements of specific crops and formulas may be targeted at critical stages of the crop cycle. In addition to being provided directly by primary fertiliser manufacturers, the UK market is supplied by a sizeable number of compounders and blenders (Dampney et al., 2003). Most UK growers use granular fertilisers purchased in bags of 500 kg and 600 kg which allows safe storage on farm and purchase at any time of the year (Dampney et al., 2003). Fertiliser application of solid materials is commonly performed with spinning disc spreaders or pneumatic fertiliser applicators whereas the application of liquids fertilisers requires conventional sprayers (Dampney et al., 2003). **Table 2.4** shows the price of a number of fertiliser products commonly used in the UK for the period 2005-09.

Table 2.4: Fertiliser prices for the period 2005-09 for selected compound and straight fertilisers commonly used in the UK, and mean annual prices of N, P_2O_5 and K_2O for the same period [Source: Nix, 2006-10]. DAP: di-ammonium phosphate; MAP: mono-ammonium phosphate; UAN: urea ammonium nitrate (solution); TSP: triple superphosphate. Prices are shown for deliveries in 500 kg or 600 kg bags; deliveries in bulk can be up to 6.5 £ t^{-1} lower.

Fertiliser type	**Fertiliser price (£ t^{-1})**				
i. Compounds	**2005**	**2006**	**2007**	**2008**	**2009**
20:10:10	141	142	156	457	222
25:5:5	136	148	153	402	198
DAP (18:46:0)/MAP (12:52:0)	---	---	---	800	290
ii. Straights	---	---	---	---	---
Ammonium nitrate (34.5% N)	145	156	169	368	190
Urea (46% N)	168	160	195	480	230
UAN (28% N)	113	99	140	390	148
TSP (47% P_2O_5)	150	148	250	690	210
Muriate of potash (60% K_2O)	138	145	165	580	360
iii. Nutrients	**------------------- Mean price (£ kg^{-1}) -------------------**				
N (Ammonium nitrate)	0.42	0.45	0.49	1.05	0.55
P_2O_5 (TSP)	0.32	0.31	0.53	1.50	0.45
K_2O (Muriate of potash)	0.23	0.24	0.28	0.97	0.60

The total consumption of nitrogen-containing fertilisers in the UK is approximately 1.2 million tonnes per year (IFA, 2000-01). Annual variations in the amount of imported nitrogen fertiliser are observed particularly for ammonium nitrate and urea which appear to be inversely related with individual demand driven by their relative prices (Dampney et al., 2003).

2.3.2 Fertiliser products

The following are some of the most commonly used fertiliser products in agricultural production in the UK. This information is available from manufacturers and supplier's websites and also Richards (2002). Chemical composition of blended and compound fertilisers is indicated in percentage of N:P_2O_5:K_2O.

i. Products for general purpose

- 20:10:10: typically used in various grassland situations and relatively low fertility soils. It has medium N concentration to suit moderate/low intensive systems such as hay production and medium levels of stocking rate. Used in a variety of grassland situations and spring cropping systems.
- 15:15:20: used in spring cereals, grass leys reseeds, main crop potatoes and grass cutting systems cultivated on soils having low P and K.

ii. Products for grass

- **Grazing:**
  - Ammonium nitrate (Nitram®): 34.5% N.
  - Urea: 46% N.
  - 25:10:0 (Early Bite®): early application of N and P with no K to avoid risk of grass stagger from early potash application.
  - 25:5:5 (Swardsman®): as above but most suitable for later applications in the spring.
- **Cutting:**
  - 20:8:12+7% SO_3 (Premier Cut®): recommended for first cut in silage production.
  - 23:4:13+7% SO_3 (MultiCut®): as above but more suitable for soils with higher soil-P indexes.
- **Cutting and grazing:**
  - 22:5:8 (Cut and graze®): double purpose fertiliser suitable for soils with low soil-K index or later applications in spring.

iii. Products for arable crops

- **Straight fertilisers:**
  - Ammonium nitrate (Nitram®): 34.5% N; the main form of straight N used in arable crops in GB since the 1960s accounting for *c*. 50% of the total nitrogen used in the UK (IFA, 2000-01).
  - Urea: 46% N; imported into the UK. Accounts for *c*. 15% of the total nitrogen used in the UK. Urea is usually less effective compared with ammonium nitrate (Chambers and Dampney, 2009).
  - Urea-ammonium nitrate (UAN): 28-30% N; fluid fertiliser having approximately 50% of total N as ammonium nitrate and 50% as urea (Chambers and Dampney, 2009). It accounts for *c*.6-8% of the nitrogen fertiliser market in the UK (IFA, 2000-01).
  - Foliar urea: 18% N; commonly used to increase the N content in grain in wheat for bread making varieties.
  - Triple superphosphate: 46% P_2O_5.
  - Single superphosphate: 18% P_2O_5.
  - Muriate of potash: 60% K_2O.

- **Blended and compound fertilisers:**
  - Ammonium sulphate: 21% N, 60% SO_3.
  - Calcium-ammonium nitrate (CAN): 26-28% N.
  - Mono-ammonium phosphate (MAP): 12-52-0.
  - Di-ammonium phosphate (DAP): 18-46-0.
  - 0:24:24: autumn sown crops on low soil P and K indexes.
  - 20:8:12+7SO_3 (Premier crop® sulphur): spring sown arable crops; e.g. maize and spring oilseed rape.
  - 0:16:36: autumn sown crops requiring additional K.
  - 0:30:15: autumn sown crops requiring additional P.
  - 26:8:8 (M24 Heartland®): medium soils requiring balanced P and K levels.
  - 26:10:0 (M24 Heavyland®): heavy soils with high soil K index.
  - Double top®: 27% N as ammonium nitrate and 30% SO_3 as ammonium sulphate; suitable for oilseed rape and winter cereals

2.4 Production of sewage sludge

2.4.1 Brief review of the wastewater treatment process

Sewage sludge is defined in Article 2(*a*) of the Sewage Sludge Directive 86/278/EEC (CEC, 1986) as:

"The residual sludge from sewage plants treating domestic or urban wastewaters and from other sewage plants treating wastewaters of a composition similar to domestic and urban wastewaters".

The purpose of wastewater treatment is to reduce the amount of organic matter, bacteria, and chemicals before it is discharged or reused and to protect the environment (Defra, 2002). A simplified wastewater treatment process is illustrated in **Figure 2.4**.

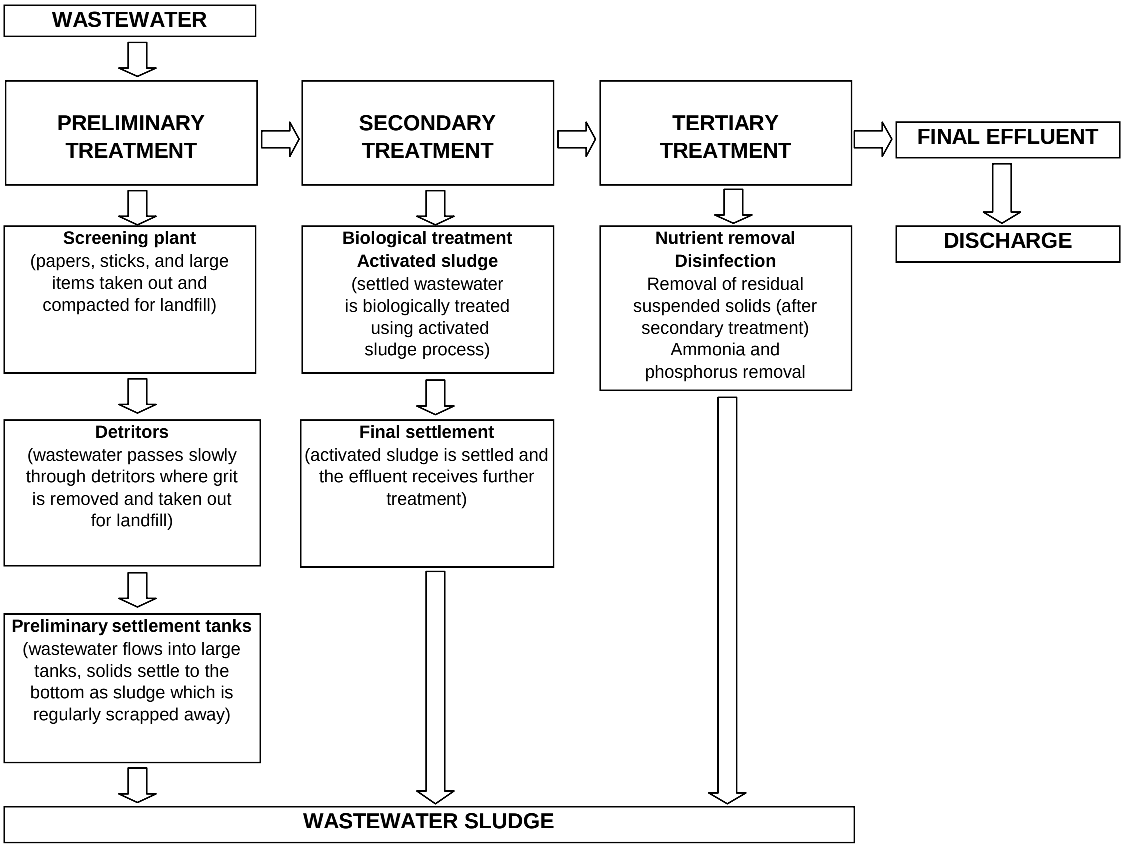


Figure 2.2: Illustration of the wastewater treatment process [Based on: Wise (1999), Metcalf and Eddy (2003), United Utilities plc (2007), Fleetwood wastewater treatment works at Fleetwood, Lancashire, UK].

Figure 2.2 shows that preliminary treatment removes part of the solids and it results in the production of some sludge. During the secondary treatment, both dissolved and suspended biological materials are significantly reduced. This is performed by aerobic bacteria which use dissolved oxygen to oxidise biodegradable compounds present in the wastewater through a process known as activated sludge. Filter beds; i.e. sewage trickled over coarse aggregate coated with bacteria, are also used (Defra, 2002).

The secondary treatment produces a biological floc which settles relatively easily; it is subsequently separated from the wastewater to produce more sludge (Metcalf and Eddy, 2003). The remaining liquor (aerated agitated liquor) has relatively low content of dissolved and suspended organic materials and it is the fraction that may undergo tertiary treatment. The aim of this phase is to enhance the quality of the final effluent before it is discharged away. Tertiary treatment is needed for the protection of sensitive water environments (Defra, 2002). When the final effluent is discharged into sensitive waters, additional removal of nitrate and phosphorus are required (Defra, 2002). At present, a number of different processes are available for removing nitrates and phosphorus from wastewaters and a comprehensive description of these is given in Metcalf and Eddy (2003).

During the tertiary treatment, the effluent may also be sand-filtrated to remove some residual suspended solids remaining after secondary treatment in addition to nutrient removal and disinfection (Metcalf and Eddy, 2003). Although nutrients removal takes place during this stage, some enhanced secondary treatments may also incorporate removal of nitrogen and phosphorus (Crites and Tchobanoglous, 1998; Metcalf and Eddy, 2003). The removal of ammonium is performed by circulating the effluent through tanks filled with expanded polystyrene beads. Microorganisms grow on the beads and break down the ammonium. Ammonium is first oxidised to nitrite and nitrate followed by a denitrification process which ends up in various nitrogen gases released to the atmosphere.

Phosphorus removal from wastewaters occurs in two ways; these are normally referred to as direct and indirect phosphorus removal. The first process can be performed by means of enhanced biological removal or by precipitation which are both specific for phosphorus removal. The second process involves the removal of phosphorus during preliminary, secondary, and tertiary treatments but without taking account of the phosphorus removed by direct processes (Wise, 1999).

Indirect removal can account for up to 50% of the total incoming phosphorus in the wastewater (Harkness and Jenkins, 1958; Williams and Coker, 1981; Van Starkenburg and Rijs, 1989; Wise, 1999). Biological removal uses phosphate accumulating bacteria which have the capacity to store large amounts of phosphate in their cells. The phosphorus enriched biomass is subsequently separated from the effluent resulting in lower content of phosphate in the treated water. Precipitation is also a common technique which consists of addition of iron, aluminium or calcium to the effluent to form insoluble phosphate compounds which are then removed from the treated water and added into the sludge. Iron and aluminium are added in the form of ferric chloride and alum respectively whereas calcium is applied in the form of lime.

Phosphorus removal by precipitation is the standard practice at United Utilities plc’s wastewater treatment works (Le, 2007; Farrant et al., 2008). Disinfection is the final stage of wastewater treatment and it may be performed to lower the number of microorganisms before it is recycled to the environment. A number of techniques are available for disinfection such as chlorination, ultraviolet treatment, ozonation, and filter membranes. The processes and methods are explained in detail in Metcalf and Eddy (2003).

2.5 Disposal of sewage sludge

2.5.1 Introduction

The total volume of sludge produced has shown a significant increase since the late 1990s (**Figure 2.3a**). In 2005, a total of 1.4 million tonnes (dry solids basis) of sewage sludge were produced in England and Wales (Defra, 2007a). This amount is set to increase to *c*.1.6 million tonnes (dry solids basis) by 2010 (Defra, 2007a) as highlighted earlier. The disposal of sewage sludge follows a number of routes. These include recycling to farmland, incineration, landfill, and land reclamation and restoration. **Figure 2.3b** shows the various disposal options of sewage sludge for England and Wales in 2005 based on Defra (2007a). Despite the large proportion of biosolids diverted to agriculture, the percentage of the total UK agricultural land area that receives biosolids regularly is *c*.1%; i.e. 80, 000 to 100, 000 hectares per year, of which approximately 60% corresponds to tillage land and the remaining 40% to grassland (Lewis, 2008).

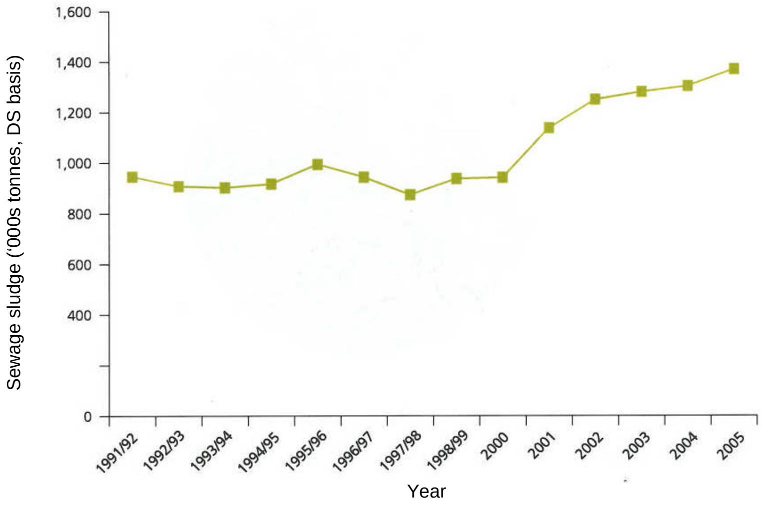


Figure 2.3a: Production of sewage sludge in England and Wales for the period between 1991-92 and 2005 [Source: Defra (2007a)].

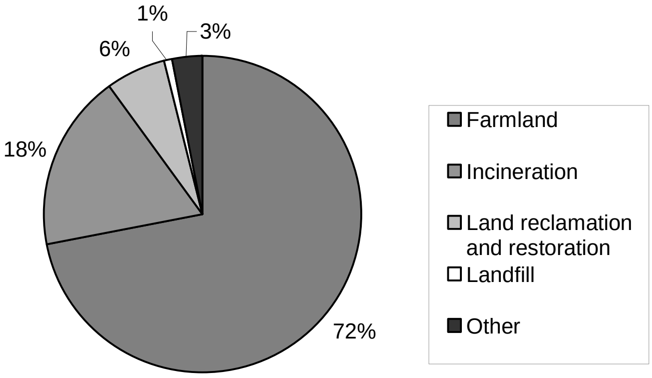


Figure 2.3b: Disposal options and sewage sludge management in England and Wales in 2005 [Source: Defra (2007a)].

Other disposal alternatives include the application of sewage sludge to industrial crops, composting, cement manufacture, and gas production. United Utilities plc is one of the largest wastewater operators in the UK providing services to *c*.7 million customers in the North West region of England and producing *c*.215, 000 tonnes (dry solids basis) per year of sewage sludge which are reduced to *c*.150, 000 tonnes (dry solids basis) after digestion (Whipp, 2007). The disposal strategy of the company is based on a dual approach of recycling to farmland and incineration which are approximately 70% and 30% respectively (Le, 2007). These two disposal options are examined in more detail **Sections 2.5.2** and **2.5.3** respectively, as they are the most important for the company's wastewater business. Landfill is also reviewed (**Section 2.5.4**) since the ashes remaining after incineration are commonly disposed of through landfill.

2.5.2 Recycling to farmland

The recycling of biosolids to agricultural land is regarded as the best practicable environmental option in most circumstances (Defra, 2007d). The European Commissioner for the Environment had manifested its intention of increasing the amount of sewage sludge that is recycled to farmland (Water UK, 2006). The position of the UK Government towards recycling has also been manifested under the ‘Waste Strategy 2000’ (Defra, 2007a). The Strategy helps to comply with targets set under the EU Landfill Directive 1999/31/EC which aims at reducing the quantities of bio-wastes diverted to landfill (Defra, 2007a). The application of sewage sludge to agricultural land is a highly regulated activity (Water UK, 2006). The most relevant legal instruments regarding the recycling of sewage sludge (biosolids) to farmland are examined in the following sections.

i. EC Sewage Sludge Directive 86/278/EEC

The EU Sewage Sludge Directive 86/278/EEC (CEC, 1986) is enforced in Great Britain through the Sludge (Use in Agriculture) Regulations 1989 (Statutory Instrument 1989 No.: 1263). This legislation regulates the land spreading of sewage sludge and implements the provisions of the Directive regarding the protection of the environment, specially the soil, when sewage sludge is used on farmland. It requires that application rates of specific heavy metals and their concentrations in the sludge (**Table 2.5**) are not exceeded beyond certain limits to avoid build up in the soil and that the risk of diseases to stock and human are minimised.

Table 2.5: Limit values for heavy metal concentrations in sludge for use in agriculture (Source: EC Sewage Sludge Directive 86/278/EEC; Moseley, 1999).

Heavy metal	Limit values (mg kg^{-1} dry matter)
Cadmium (Cd)	20-40
Copper (Cu)	1000-1750
Nickel (Ni)	300-400
Lead (Pb)	750-1200
Zinc (Zn)	2500-4000
Mercury (Hg)	16-25

The Directive promotes the beneficial use of sludges and imposes uniform and mandatory standards throughout Europe. The salient points of the Directive, relevant to the application of biosolids to arable land are summarised below:

- The concentration of heavy metals in sludges used in agricultural land must not be exceeded to avoid build up in the soil,
- There must be a period of time between application of sewage sludge and grazing or harvesting (see the Safe Sludge Matrix in **Appendix 2.2** for full details),
- Treatment of sewage sludge is required when used in agricultural land although raw sludge may be applied providing it is injected or incorporated into the soil.

The Sludge Regulations 1989 back up the statutory management requirement (SMR No.: 3) for sewage sludge under cross compliance (Defra, 2006a). These regulations are subjected to amendment implying that conventional or enhanced treatment will become a statutory requirement before sludges are used on land for food production. The primary focus of amended regulations is to provide protection of the food chain from pathogens and reassurance to stakeholders (Lewis, 2008). The secondary purpose is to secure the sustainable re-use of sewage sludge (biosolids) in agricultural land (Lewis, 2008). Further amendments to the Sludge (Use in Agriculture) Regulations 1989 will incorporate the guidelines specified under the Safe Sludge Matrix.

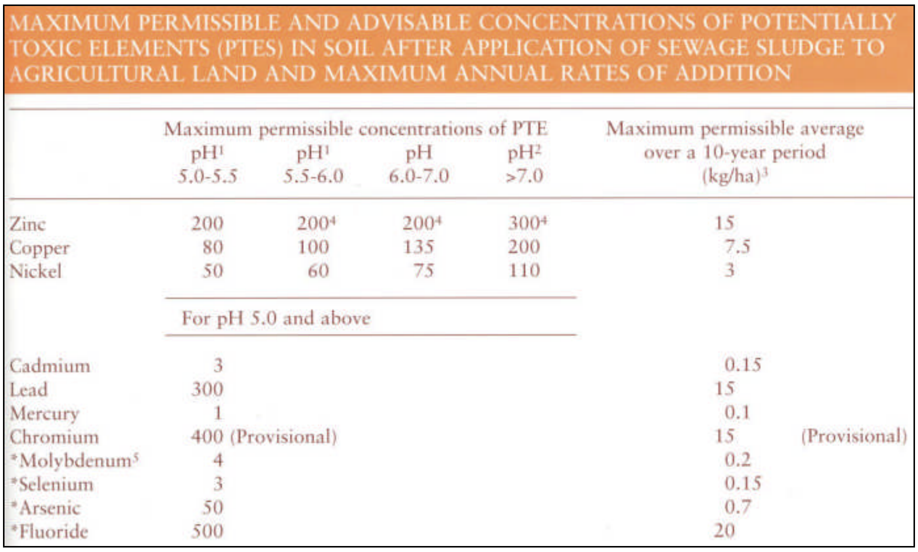
ii. Code of Practice for Agricultural Use of Sewage Sludge

The Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1990) was last revised in 2001 and it reinforces the EU Sewage Sludge Directive 86/278/EEC. It applies to the utilisation of biosolids in agricultural land in the UK. This Code was drawn to complement the Sludge (Use in Agriculture) Regulations 1989 (SI No.: 1263) which includes Great Britain, and also the Sludge (Use in Agriculture) Regulations (Northern Ireland) 1990 (SR 1990, No.: 245) which enforce the provision of the EC Directive 86/278/EEC on the protection of the environment and in particular of the soil when sludges are use in agricultural production. Its recommendations are supported by sound scientific knowledge and in accordance with relevant regulatory instruments.

iii. Code of Good Agricultural Practice for the Protection of Water, Soil, and Air

The Code of Good Agricultural Practice for the Protection of Water, Soil, and Air (Defra, 2009c) replaced the individual Water, Soil, and Air Codes previously produced by MAFF (1998a-b-c) and reinforces the Sludge (Use in Agriculture) Regulations 1989 (Moseley, 1999). The Code was designed to help farmers delivering good standard of environmental protection.

It also provides a number of key actions that can be undertaken to enhance the quality of water, soil, and air and to help land managers in meeting legal obligations including those listed under cross compliance. By observing both legal requirements and the Code, the water quality standards set under the EC Water Framework Directive 2000/60/EC are likely to be achieved by 2015 (Defra, 2009d). Although not all of the new Code's components are mandatory, Section 97 of the Water Resources Act 1991 lists the Code of Good Agricultural Practice for the Protection of Water as statutory. The Water Resources Act 1991 contains the provisions designed to prevent water pollution and allows prosecution to be conducted against those responsible for polluting water courses. In addition, Section 2.3 (paragraphs 69-83) of the new Code is statutory under the Nitrates Directive 91/676/EEC. It is important to highlight that the former Soil Code (MAFF, 1998b) provides reference values for maximum permissible levels of heavy metals in soil; these are quoted in **Figure 2.4** (after MAFF, 1998b).



MAXIMUM PERMISSIBLE AND ADVISABLE CONCENTRATIONS OF POTENTIALLY TOXIC ELEMENTS (PTES) IN SOIL AFTER APPLICATION OF SEWAGE SLUDGE TO AGRICULTURAL LAND AND MAXIMUM ANNUAL RATES OF ADDITION

	Maximum permissible concentrations of PTE				Maximum permissible average over a 10-year period (kg/ha)[3]	
	pH[1] 5.0-5.5	pH[1] 5.5-6.0	pH 6.0-7.0	pH[2] >7.0		
Zinc	200	200[4]	200[4]	300[4]	15	
Copper	80	100	135	200	7.5	
Nickel	50	60	75	110	3	
	For pH 5.0 and above					
Cadmium	3				0.15	
Lead	300				15	
Mercury	1				0.1	
Chromium	400 (Provisional)				15	(Provisional)
*Molybdenum[5]	4				0.2	
*Selenium	3				0.15	
*Arsenic	50				0.7	
*Fluoride	500				20	

Figure 2.4: Maximum permissible concentrations of potentially toxic elements in soil following application of sewage sludge in relation with soil pH (Source: MAFF, 1998b).

iv. EC Urban Wastewater Treatment Directive 91/271/EEC

The Urban Wastewater Treatment Directive 91/271/EEC (CEC, 1991b), including later amendments, regulates both wastewater collection and treatment from domestic and industrial sources, and its subsequent disposal. The Directive is implemented through the Urban Wastewater Treatment (England and Wales) Regulations 1994 (Statutory Instrument No.: 2841) and amended Regulations 2003 (Statutory Instrument No.: 1788). The aim of the Directive 91/271/EEC is to set out the standards for the collection and treatment of urban wastewater throughout Europe.

In addition, the Directive imposes a ban on sea dumping of sewage sludge from the end of 1998. Further, it is a requirement under the Directive that sludges should be re-used whenever appropriate and that existing disposal routes should minimise adverse effects on the environment.

v. EC Nitrates Directive 91/676/EEC

The EC Nitrates Directive 91/676/EEC was adopted to prevent and reduce water pollution caused by nitrate losses from agriculture. The Directive is enforced through the Nitrate Pollution Prevention Regulations 2008 (Statutory Instrument No.: 2349). These regulations replaced the Protection of Water against Agricultural Nitrate Pollution (England and Wales) Regulations 1996 and the Nitrate Vulnerable Zones (Additional Designations) England (No.: 2) Regulations 2002. The Nitrate Regulations identified areas having, or likely to have, nitrate pollution; i.e. nitrate concentration in surface or groundwater in excess of 50 mg l^{-1}. These areas are known as Nitrate Vulnerable Zones (NVZs) and presently occupy *c.*70% of the land area in England. In addition, a number of rules for specific farming practices were set out and they must be observed within NVZs. Those relevant to biosolids application are summarised below:

- Increased restrictions on organic manures application; i.e. extended closed periods as follow:
  - Grassland: 1st September – 31st December (sandy and shallow soils), and 15th October – 15th January (all other soils),
  - Tillage land: 1st August – 31st December (sandy and shallow soils), and 15th October – 15th January (all other soils),
- Reduction in whole farm manure nitrogen loading to 170 kg [N] ha^{-1} $year^{-1}$,
- Written assessment of spreading location and record keeping,
- Certain manure application techniques were abolished,
- Crop nitrogen requirement limit and maximum nitrogen application for each crop; i.e. N_{max}, were established,
- Definition of sloping ground and risk assessment for land application.

Rules apply from 1st January 2009 for NVZs as designated in 2002 and from 1st January 2010 for NVZs designated in 2008. Compliance with these regulations is also a statutory management requirement (SMR No.: 4) under cross compliance.

vi. Safe Sludge Matrix

An agreement between Water UK, which is the representative body of the water industry in the UK, Sewage Operators, and the British Retail Consortium, was reached on 31st December 1998. As a result, a document entitled Safe Sludge Matrix (**Appendix A.2.2**) was produced to set out some guidelines for the application of sewage sludge (biosolids) to farmland (ADAS et al., 2001a). The main implications of this agreement are summarised below:

- Application of untreated sewage sludge on agricultural soils used for food production is terminated;
- Conventionally treated sludge can only be applied on combinable crops, and ploughed down or injected into grassland and no grazing should take place during the season of application;
- Only enhanced treated sludge; i.e. that achieving ≥99.9999% pathogens destruction, can be applied to all crops and grassland although some intervals between successive applications may be respected.

The enforcement of the Safe Sludge Matrix guarantees growers a safe product which should be an incentive to increase current levels of biosolids recycled to agricultural land. In this respect, Sturt (2007) and Reeves (2007) acknowledged that farmers' perception in the use of biosolids in agriculture is relatively poor. The risk of heavy metals accumulation in the soil and practicality issues associated with the use of bulky organic-based materials has also contributed to this poor perception. This is certainly a barrier to increasing current levels of biosolids up take by farmers. Crathorne (2007) highlighted the role of alternative, and perhaps more reliable, organic wastes to sewage sludge in competing for the land bank for recycling. In recent years significant investments on sludge and wastewater treatment were made by the water industry which resulted in enhanced quality of the wastewater treated and biosolids produced (Water UK, 2006). Current legislation appears to be the main driver for sewage sludge management and disposal; hence, the water industry needs to be able to accommodate to both existing and new legislation in order to secure the agricultural route for disposal. Relying upon recycling for about three quarters of the total sewage sludge production means that the wastewater business for United Utilities plc may be exposed to a high risk. The challenge facing the water industry is how to sustain the agricultural route and move away from more expensive and less environmentally friendly disposal options. The development of enhanced biosolids products that better suit the needs of modern agricultural production is a key aspect to protecting the business and facilitating the recycling through agriculture.

vii. Fertiliser value of sewage sludge (biosolids)

The following is an example of the potential financial savings that could be made when using biosolids in agricultural crops. This has been taken from RB209 (MAFF, 2000). The prices of the two primary nutrients in biosolids were subsequently corrected to 2010's prices (Nix, 2010) and the example given in the book was recalculated based on the same assumptions. RB209 indicated that the application of digested cake to a winter wheat crop at a rate of 30 t ha^{-1} can result in financial savings of up to 85 £ ha^{-1} (assuming price of nitrogen and phosphate at 0.30 and 0.30 £ kg^{-1} respectively). Application of digested cake at this rate can supply up to 225 kg [N] ha^{-1} of which *c.*20 kg [N] ha^{-1} will be available to the crop for applications in the autumn (incorporated before winter wheat, and assuming that nitrogen availability is approximately 10% of the total nitrogen applied). In addition, this application rate can provide approximately 270 kg [P_2O_5] ha^{-1} which represents (at the prices mentioned above) *c.*80 £ ha^{-1}. Converted at current (2010's) prices and based upon the calculations made in RB209, the potential financial savings would be approximately 195 £ ha^{-1} (i.e. 20 kg [N] ha^{-1} at 0.62 £ kg^{-1} is 12.5 £ ha^{-1} plus 270 kg [P_2O_5] ha^{-1} at 0.68 £ kg^{-1} is 185 £ ha^{-1} approximately). This provides an indication of the value of nutrients contained in biosolids and it emphasises the need to make a sustainable use of these materials.

2.5.3 Incineration

Incineration is the combustion of sewage sludge which results in the reduction of sludge volume (Moseley, 1999). Incineration of sewage sludge is governed by the EU Waste Incineration Directive 2000/76/EC (EC, 2000). It may be arguably that the process of incineration does not align with Article 14 of the EU Urban Wastewater Treatment Directive 91/271/EEC which establishes that 'sludges arising from wastewater treatment shall be re-used whenever appropriate'. The UK Government manifested its intention of cutting back carbon dioxide emissions by 20% in 2010 (Defra, 2007e) which, inevitably, will affect the amount of sewage sludge disposed of through incineration. Rowlands (1998) stated that incineration is relatively clean with respect to emissions. However, the process can leave up to 30% of the waste in the form of ashes which require careful management and disposal (EC, 2003). Ashes resulting from the incineration process are normally disposed of through landfill as a beneficial outlet has not been found (Moseley, 1999). Whipp (2007) highlighted that obtaining planning permissions to expand existing incineration capacity is becoming increasingly difficult and that alternatives for disposal should be sought elsewhere to deal with the projected increase in sewage sludge production.

2.5.4 Landfill

Landfill of sewage sludge consists of dumping of de-watered sludge at specific sites (Moseley, 1999). The activity is regulated by the EU Landfill Directive 1999/31/EEC (CEC, 1999) which is implemented in England and Wales through the Landfill (England and Wales) Regulations 2002. The aim of the Directive is to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of waters, soil and air, and the global environment and also to reduce the amount of organic materials disposed through landfill. The UK has committed to cut back the amount of waste landfilled to 75% of that produced in 1995 by 2010 (Defra, 2007b) with further reductions set afterwards. In addition, disposal through landfill is becoming increasingly expensive which indirectly favours the recycling of biosolids to agriculture (Oliver, et al. 2005). It is anticipated that this route will be virtually close for the disposal of sewage sludge driven mainly by current legislation in force including the EU Urban Wastewater Treatment Directive 91/271/EEC. Recycling of biosolids to agricultural land provides a long term sustainable solution to the disposal of sewage sludge. Incineration and landfill are expensive and current regulatory framework imposes increasing restrictions to these routes.

2.5.5 Sewage sludge (biosolids) treatment

The treatment of biosolids is a key requirement prior to their application to land (ADAS et al., 2001a). A comprehensive review of the processes for wastewater sludge treatment was conducted by Wise (1999); the author stated that the type of process will determine the characteristics of the sludge, in particular, phosphorus form and quantity. These processes, for the treatment of raw wastewater sludge include (after Wise, 1999): **a.** thickening (gravity/mechanical); **b.** stabilisation (aerobic/anaerobic digestion); **c.** conditioning (chemical/mechanical); **d.** dewatering (natural/mechanical e.g. belt press or centrifuge/thermal). In addition, a brief description of some of the processes commonly used is provided below (after Moseley, 1999; Metcalf and Eddy, 2003):

i. Pasteurisation

For disinfection of wet sludges, (heat) pasteurisation is conducted at 70°C for 30 minutes to inactivate parasitic ova and cysts or a minimum of four hours at 55°C followed in all cases by primary, mesophillic, anaerobic digestion (Moseley, 1999; Metcalf and Eddy, 2003). There are two methods used for pasteurisation of liquid sludges: direct steam injection, and indirect heat exchange. Full description of these techniques is given in Metcalf and Eddy (2003).

ii. Mesophillic and thermophilic anaerobic digestion

Digestion involves the breakdown of organic matter content in the sludge to simpler compounds and eventually to carbon dioxide, water and anions (nitrate, sulphate, and phosphate) (Wise, 1999). Mesophillic anaerobic digestion is performed at 37°C (Wise, 1999) whereas thermophilic digestion is conducted at temperatures between 49°C and 57°C. This latter type of digestion is faster than mesophillic as biochemical reaction rates increase with temperature (Metcalf and Eddy, 2003). The main advantage of this process is the relatively high rate of bacterial destruction but it also has high energy requirements (Metcalf and Eddy, 2003).

iii. High rate enzyme hydrolysis

A process called high rate enzyme hydrolysis was developed at United Utilities plc to control the pathogens load in biosolids. This process is conducted during the anaerobic digestion and provides biosolids with up to 99.9999% pathogens destruction. A complete description of the process is given in Le et al. (2006). The adoption of this technology facilitated the compliance by the company with some of the guidelines outlined in the Safe Sludge Matrix.

iv. Lime stabilisation

It involves the addition of lime to decrease the number of microorganisms; it results in pH rising to about 12 which needs to be maintained at that level for approximately 2 hours. It results in biosolids being subsequently useful for application in soils with low pH (Moseley, 1999).

2.6 Nutrients dynamics in agricultural systems

2.6.1 Introduction

A number of nutrients are needed for plant growth and development and they all should be considered essential (Archer, 1988). A differentiation can be made between primary nutrients, secondary nutrients, and micronutrients depending on the amount required by the plant (Darwich, 1998). This section examines the nutrient dynamics in agricultural systems and focuses upon nitrogen and phosphorus.

2.6.2 Mechanisms of nutrients uptake by crops

A detailed explanation of the complex physiological processes involved in the uptake of plant nutrients and their assimilation is provided by Mengel and Kirkby (1987). Nielsen (1983) indicated that there are a number of factors controlling the efficiency of nutrients uptake by plants which include nutrients' concentration in the rhizosphere and root density.

The process of nutrients uptake by plants involves the use of energy which is provided by cell metabolism (Mengel and Kirkby, 1987). Plant nutrients can be transported from the soil matrix to plant roots via two main mechanisms: mass flow and diffusion. The first occurs when nutrients are transported in solution by means of a water flow from the soil matrix to the roots (Tognetti et al., 2005) and it is therefore driven by plant transpiration (Kirkby et al., 2009). Hence, the amount of a particular nutrient taken up by the plant is dependent on the volume of water entering the roots and the concentration of the nutrient in the solution (Tognetti et al., 2005). The water-flow to plant roots is directly linked to the transpiration rate of the plant and the soil water content. Therefore, nutrient uptake by mass flow is controlled by conditions affecting the transpiration rate and the moisture content of the soil. The concentration of a nutrient in the soil depends on both solubility in the soil solution and its availability in the soil (Tognetti et al., 2005). Strebel and Duynisveld (1989) estimated that mass flow can account for up to 33% of the total nitrogen transported to the roots in sugar beet and cereal crops during the period of maximum demand by the crop. Diffusion occurs when plant nutrients move according to their relative concentrations between the soil solution in the proximity of the root and the root surface and it is induced by nutrient removal during uptake (Barber et al., 1963; Kirkby et al., 2009). This mechanism is affected by a gradient in the nutrients concentration and also by the distance between the two points (Tognetti et al., 2005). Hence, diffusion becomes significant only within short distances from the root surface.

Plant nutrients reach the roots by means of both processes; however, those nutrients with higher solubility; e.g. nitrogen (as NO_3^-), mass flow is quantitatively a more important process compared with diffusion. Similarly, for nutrients having lower solubility/mobility; e.g. phosphorus, diffusion can be more important than mass flow. Barber et al. (1963) suggested that up to 99% of the nitrogen is transported to the roots by mass flow whereas for phosphorus diffusion accounts for approximately 95%. Nitrate transport to the roots by diffusion becomes increasingly important only when its concentration in the soil solution decreases (Tognetti et al., 2005). Under certain conditions; e.g. low transpiration rate, the proportion of nutrients reaching the surface of the roots by mass flow is reduced and diffusion becomes relatively more important. The implication of these processes is that the efficiency of plant uptake of lower solubility/mobility nutrients increases when they are applied in the proximity of the growing root; i.e. localised supply (Drew, 1975).

There is also a third mechanism for nutrient uptake known as root interception; it occurs as a result of the growth of the root through the soil which makes contact with plant nutrients (Darwich, 1998). The release of hydrogen ions by plant roots may be involved in this process (Tognetti et al., 2005). High concentration of hydrogen ions around the roots would promote the exchange of cations with clay particles in contact with plant roots. Cations would be first released from clay particles and replaced by hydrogen ions and subsequently attached to the root before being absorbed by the plant (Tognetti et al., 2005). This mechanism appears to be more important for calcium and magnesium (Barber, et al., 1963). The relative importance of each mechanism largely depends on the crop and also the soil type (Barber et al., 1963).

In some cases, nutrients can also enter the plant through the leaves (foliar absorption); this mechanism of nutrients uptake has been shown to be effective to correct micronutrients deficiencies in foliar applications; e.g. deficiencies of iron, cupper, or manganese (Torri et al., 2005). There is also evidence of foliar absorption through stomata. For example, absorption of sulphur as SO_2 (Paul, 1974; Fowler and Unsworth, 1979), and ammonia following volatilisation of nitrogen from surface applied urea (Ping et al., 2000). The physiological factors influencing ammonia exchange between the leaves and the atmosphere are discussed in detail in Schjøerring et al. (1998). Foliar application of urea to wheat was shown to have a significant effect on nitrogen concentration in grain with nitrogen being efficiently transported from the leaves and on to the heads (Smith et al., 1991; Gooding, 2005).

2.6.3 Crop responses to applied nutrients

The relationship between increases in crop yield and additional fertiliser is known as fertiliser response curve (FAO, 1966). The increments in crop yield from each successive application of a given plant nutrient becomes progressively smaller; ultimately, a point in the curve is reached where an additional input of fertiliser does not result in the yield of the crop increasing significantly to outweigh the cost of the nutrient applied (Troeh and Thompson, 1993). Various mathematical functions have been used to show diminishing returns and some of the common functions used are discussed in FAO (1966). For arable crops a quadratic function is usually preferred since it gives acceptable fits in most cases (Abraham and Rao, 1965). A criticism to response curves is that they are site and year specific (Russell, 1988; Olfs, 2009); however, historic field data can contribute to overcome this issue. Using a quadratic equation to describe a nitrogen response curve and following the procedure proposed by James and Godwin (2003) for cereal crops, the nitrogen fertiliser rate at which the maximum grain yield is obtained can be calculated by equating the first order differential to zero:

Given,

$$y = a + bx - cx^2 \tag{2.1}$$

Where: *a, b,* and *c* are the regression coefficients, *y* is the crop yield, and *x* is the rate of nitrogen applied to the crop.

Then,

$$\frac{dy}{dx} = b - 2cx' = 0 \tag{2.2}$$

Therefore,

$$x' = \frac{b}{2c} \tag{2.3}$$

Where, *x'* is the nitrogen fertiliser rate at which the maximum yield is obtained. The most economic rate of nitrogen (MERN) is obtained when **Equation [2.2]** is equated to the price ratio, R_P (James and Godwin, 2003) which is defined as the price of the nitrogen fertiliser, P_N , divided by the price of the crop, P_C , (Kachanoski et al., 1996):

Thus,

$$b - 2cx' = R_P \tag{2.4}$$

Then,

$$R_P = \frac{P_N}{P_C} \tag{2.5}$$

And,

$$MERN = \frac{(b - R_P)}{2c} \tag{2.6}$$

The price ratio, R_P , is simply the break even ratio (B_E) and it indicates the extra return of the produce that just covers the extra unit of nitrogen added. At this point, the economic return from applied nitrogen is maximised. Nitrogen rates below MERN result in economic losses since crop yield is restricted by nitrogen supply whereas higher nitrogen rates than MERN provide the opportunity for nitrogen losses, especially through leaching, as above this point the efficiency at which nitrogen is converted into grain yield starts falling.

Equally, excess nitrogen supply can cause lodging of the crop (Addiscott et al., 1991) with drastic consequences in crop yield and quality. When the B_E ratio is increased, for example as a result of increased fertiliser price, then the MERN is lower to allow for the same rate of economic return from the applied fertiliser. The same principle may be applicable for other plant nutrients as long as the response curve of the crop is quadratic and the cost of the applied nutrient is known.

Experimental work on grass responses to nitrogen application was undertaken by Morrison et al. (1980), Doyle and Elliot (1983), Large et al. (1983) and Baker (1986) among others. Dry matter yield (DM) per unit area in grass crops has been reported to respond linearly up to application rates of *c*.300 kg [N] ha^{-1} (Holmes and Aldrich, 1957; Morrison et al., 1980; Frame et al., 1989; Fisher and Jewkes, 2009). Typical increments are between 15 to 30 kg [DM] ha^{-1} per kg of additional nitrogen depending on the fertility status of the soil and climate (Fisher and Jewkes, 2009). Above those nitrogen rates, the response is not longer linear and starts to decline to reach maximum yields at rates of *c*. 500-600 kg [N] ha^{-1} per year (Fisher and Jewkes, 2009).

In dairy systems and grass cut for silage it is accepted that where the response of the grass declines to *c*. 7.5 kg [DM] ha^{-1} for each additional kg of nitrogen applied it represents the B/E; i.e. the target yield and nitrogen application rate (MAFF, 2000; Fisher and Jewkes, 2009). In beef and other less intensive grazing regimes, this figure is *c*.10 kg [DM] ha^{-1} (MAFF, 2000). At this level of nitrogen fertilisation approximately 90% of the maximum grass yield is reached using less than 60% of the total nitrogen required for maximum yield (Fisher and Jewkes, 2009). A response of 10 kg [DM] ha^{-1} was also used by Morrison et al. (1980) to identify the optimum nitrogen application rate in rye grass.

2.6.4 Application of biosolids and mineral fertilisers

Several methods are available for the application of biosolids to land. Liquid sludges (dry solids content in the range of 3 to 12%) can be applied either on the soil surface which may or may not be subsequently incorporated and can also be injected into the soil (Bowden, 1996). The application on the surface can be performed by means of a splash plate spreader or a dribble bar as shown in ADAS et al. (2001b). The first type consists of a tanker (vacuum or pumped) which is pulled by a tractor and has a splash plate fitted at the rear of the tanker which spreads the liquid over the surface. The dribble bar can operate with an umbilical hose supply or combined with a tanker. Other surface spreading techniques includes for example the use of trailing shoe spreaders and manure guns (ADAS et al., 2001b).

The use of dribble bars has the advantage over the splash plate spreaders of being able to reduce odour nuisance to a greater extent (Stroud and Phillips, 1988). Legislation such as the Sludge (Use in Agriculture) Regulations 1989 and the Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1990), and increasing concerns over environmental related issues; e.g. odour nuisance, the risk of pollution of water courses through surface runoff and ammonia emissions, led to further development and implementation of injection techniques (Warner et al., 1991; Moseley, 1999). It also became increasingly important to make improvements in the use of nutrients available in sludges (Pullen et al., 2004a). Early work on the subject had been undertaken by Smith et al. (1973) among others, and vast amount of research into the design of injector tines was later conducted; e.g. Warner and Godwin (1988), Warner et al. (1991), Moseley et al. (1998), Godwin et al. (1998) and Pullen et al. (2004b). These studies were based upon earlier investigations into soil tillage and also the injection of anhydrous ammonia to grassland; e.g. Godwin (1974); Godwin and Spoor (1977); Spoor and Godwin (1978) and Ahmed and Godwin (1983). Deep injection techniques (150-450 mm) were initially developed and included the work by Pullen (1976) and Negi et al. (1978).

Subsequently, shallow injection techniques (≤150 mm) were developed and proved to be equally efficient in terms of ammonia emissions and even more effective in reducing energy requirements and damage to established crops (Phillips et al., 1990; Hann et al., 1992; Moseley, 1999). It was also demonstrated that the benefits of reducing ammonia emissions were not offset by increases in nitrate leaching. The injection of biosolids can be performed in a number of ways which include the use of the following equipment: **a.** Pressure discharge tanker with injectors (pulled or self-propelled); **b.** Trailed umbilical hose connecting a storage tank placed off-field with sludge applicators mounted on a tractor; and **c.** Tanker pulled by a tractor with a hose connecting this tank with applicators mounted on a second tractor and working in tandem. The application of biosolids with larger dry solids content (≥25%) than liquid sludges can be performed using the same machinery as that used for the application of farm yard manure; e.g. muck spreaders having rear or side discharge (ADAS et al., 2001b). Nix (2010) reported that the costs of application of slurries (contractor’s charge) are £35.75 per hour (tanker), £58.40 per hour (umbilical hose) and £51.75 per hour for injection.

Work rates for injection of biosolids may be comparable to those of subsoilling (6 to 10 hectares per day for working width between 3 to 5 m; Nix, 2010) while operating in the field but overall they may be marginally lower when taking account of the time required for re-filling the tanker. Higher work rates may be achieved with shallow compared with deep injection.

Typical work rates of broadcast spreading of solid fertilisers are between 30 to 40 hectares per day (assuming 8 hours per day, and including loading and carting with working widths typically between 18 m to 24 m) but works rates in the range of 25 to 60 hectares per day are also reported depending on the tonnage delivered and the capacity of the spreading equipment (Nix, 2010). Cost of spreading of FYM, which could be taken as reference for the spreading of biosolids in the form of cake, are approximately £36 per hour (tractor and spreader) plus £30 per hour (tractor and loader) as reported by Nix (2010). The working width may vary depending on the content of solids in the material and the characteristics of the spreading equipment but they may be between 8 and 12 m and they would operate at rates of approximately 15 to 20 hectares per day (O'Dell, 2010).

Mineral fertilisers can be applied using four different types of spreading equipment which include: **a.** Spinning disc; **b.** Pneumatic; **c.** Oscillating spout; and **iv.** Sprayers (Dampney et al., 2003). A brief description of the main characteristics of each type of fertiliser spreading equipment is given below based on the work reported by Dampney et al. (2003). Spinning discs are by large the most common type of fertiliser spreaders (*c*.65%) in arable and grassland situations in farms larger than 50 ha (MAFF, 2000). The main advantages of this type of equipment are low capital cost and versatility as they can operate reasonably accurately in tramlines spaced at 24 m with a range of fertiliser types. Dampney et al. (2003) stated that the basic of functioning consists of producing a triangular transverse mass distribution pattern with a wider base than the desired bout width so that the overlapping with contiguous bouts results in a uniform distribution pattern across the whole working width.

Pneumatic spreaders have the advantage of being able to work more accurately than spinning disc spreaders when the fertilisers have small particle size distribution or low density. The effect of the wind is also reduced and more control over the spreading width can be achieved compared with spinning discs. Miller et al. (2000) also demonstrated that a low coefficient of variation (e.g. ≤10%) can be obtained with the use of pneumatic spreaders for application of urea based fertilisers at working width of 24 m. Among the main disadvantages of pneumatic equipments are the relatively high capital and maintenance costs. Some operational limitations were also reported with regards to the weight of the equipment when working on soft soil conditions and also when using materials having low flowability. The use of oscillating spout spreaders is more common (*c*.20%) in grassland situations and also in arable having a narrower tramline arrangement; typically 12 to 18 m apart.

Fluid fertilisers are usually applied with the same sprayer equipment used for the application of agrochemicals. Sprayers can perform with a high degree of accuracy of distribution at even wider working widths than spinning disc equipment; e.g. tramlines set at 30-36 m apart, thereby providing higher work rates. Typical coefficients of variation for sprayers were found to be *c*.5% compared to *c*.10% typically encountered for spinning discs fertiliser spreaders.

2.6.5 Nitrogen

A simplified overview of the nitrogen cycle is shown in **Figure 2.5**. Nitrogen is the nutrient demanded by crops in largest quantities (Black, 1968; Ferraris, 2008 & 2009) and it is well documented that shortages of nitrogen determine losses of crop yield. Nitrogen is needed for the synthesis of chlorophyll which is vital for the photosynthesis process (Darwich, 1998). Its deficiency results in reduced photosynthetic activity, reduced efficiency in the interception of sunlight and affecting the conversion of radiation into biomass and crop yield (Uhart and Andrade, 1995). Nitrogen is a key component of proteins, vitamins, and enzymes which control complex metabolic processes (Darwich, 1998; Taiz and Zeiger, 1998; Echeverria and Sainz-Rozas, 2005). It is also present in the DNA, RNA, and organic compounds used to store/transfer energy such as ATP and NADP (Tognetti et al., 2005).

In cultivated soils, crop residues and roots are the main source of carbon and nitrogen to the soil system (Echeverria and Sainz-Rozas, 2005). The total nitrogen content in the top soil for most cultivated soils varies between 0.03% and 0.35% (w w^{-1}) reaching up to 2.5% (w w^{-1}) in organic soils (Darwich, 1998). Bremer (1975) highlighted that between 95% and 99% of the total nitrogen in the top soil occurs in organic forms as part of the soil organic matter. The remaining soil nitrogen consists of inorganic compounds whose low availability usually demands for exogenous nitrogen applications to sustain adequate levels of crop production. Inorganic nitrogen has a very short life and any excess not taken up by the growing crop is likely to undergo further transformations such as volatilisation or denitrification or be irreversibly lost from the soil-root system by leaching (Cooke, 1982; Rodriguez, 2008). The efficient use of nitrogen from fertilisers and organic amendments, including biosolids, requires understanding of the various processes that take place in the nitrogen cycle and the selection of appropriate application methods. These processes are examined in more detail in the following sections.

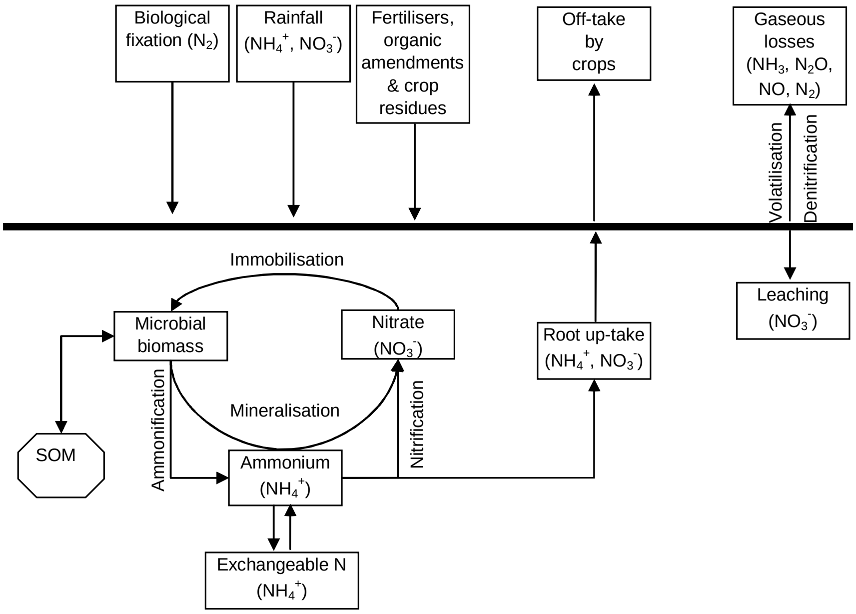


Figure 2.5: Simplified representation of the nitrogen cycle (from Archer, 1988; Bosshard et al., 2009); [SOM: soil organic matter].

2.6.6 Nitrogen mineralisation and immobilisation

Mineralisation of soil organic nitrogen is a complex process (Black, 1968). Early studies on this matter were conducted by Harmsen and Van Schreven (1955) and Harmsen and Kolenbrander (1965) among others. Mineralisation involves the conversion of organic nitrogen into mineral nitrogen (Rodriguez, 2008). It is a three stages process; namely, aminisation, ammonification and nitrification, which is conducted by soil microorganisms (Tisdale et al., 1990). The mineralisation process is shown in **Figure 2.6.**

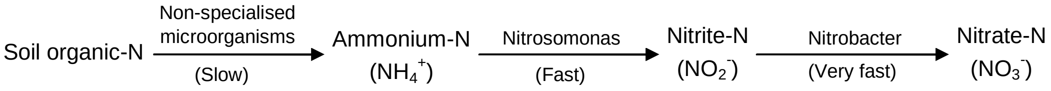


Figure 2.6: Mineralisation of soil organic nitrogen (from Black, 1968; Darwich, 1998).

The mineralisation process is controlled by a number of factors such as the size of the organic substrate undergoing decomposition, soil temperature and soil moisture content (Echeverria and Sainz Rozas, 2005). The velocity of the process depends largely on the release of organic-N compounds and the subsequent conversion to ammonium-N (NH_4^+) since the other two stages occur relatively fast. This is the reason why ammonium-N and nitrite-N (NO_2^-) do not normally accumulate in the soil in large quantities.

Organic-N is usually found in the soil as amino-N (NH_2^-) (Follet et al., 1981). The release of ammonium from organic nitrogen compounds occurs when heterotrophic microorganisms break down organic substrates to utilise organic carbon as a source of energy. Part of the nitrogen released is incorporated into the own microorganisms biomass and any unused ammonium is released to the soil and further oxidised to produce nitrite and nitrate. Nitrosomonas and Nitrobacter are respectively the microorganisms responsible of this process (Grant and Long, 1989). As these bacteria are autotrophs; therefore, do not rely on the oxidation of organic compounds to obtain energy (Black, 1968), they can utilise carbon dioxide as a source of carbon. This carbon is subsequently reduced using the energy released from the oxidation that takes place in stages two and three (**Figure 2.6**); i.e. formation of nitrite (NO_2^-) and nitrate (NO_3^-). When a substrate undergoing decomposition contains very small amount of nitrogen in relation to carbon, microorganisms will take up mineral nitrogen from the soil to satisfy their nitrogen requirement (Mary and Recous, 1994).

The process by which mineral nitrogen is incorporated into soil microbial biomass is known as immobilisation (Barraclough and Smith, 1987). Thus, this process is reversible since formation of mineral nitrogen occurs with the opposite process of immobilisation (Black, 1968). Net nitrogen mineralisation is therefore the difference between total nitrogen mineralised and total nitrogen immobilised (Murphy et al. 2003). The carbon to nitrogen ratio (C:N ratio) of organic materials applied to the soil is also regarded as an important factor affecting both nitrogen mineralisation and immobilisation. An equilibrium between mineralisation and immobilisation may be reached when the C:N is in the range of 30-20:1 (Tisdale et al., 1990; Addiscott et al., 1991; Troeh and Thompson, 1993; Darwich, 1998). Generally, an increase in the C:N ratio results in soil available nitrogen being immobilised whereas lower ratios would promote mineralisation. The application of organic amendments to the soil with relatively large C:N ratios; e.g. C:N ratios >15, produce limited soil nitrogen availability as a result of nitrogen immobilisation (Gutser et al., 2005). Swift et al. (1979) indicated that the C:N tend to decrease as decomposition of organic matter progresses. Harmsen and Van Schreven (1955) also suggested critical nitrogen contents in the substrate between 1.2% and 2.6% (w w^{-1}) below which immobilisation would take place. With particular regards to sewage sludge, Barbarika et al. (1985) highlighted that the C:N ratio is a valuable determination to predict nitrogen mineralisation. Studies on sludge decomposition have shown that the process is affected by the type of sludge and composition, the quantity applied, soil temperature, timing of application, and treatment (Sommers et al., 1976; Tester et al., 1977).

Anaerobic digestion of sewage sludge narrows the C:N ratio of the sludge since the digestion process consumes carbon (Metcalf and Eddy, 2003). This, results in increased mineralisation rate following application to land compared with untreated sludge. Studies on nitrogen mineralisation have often been conducted using incubation techniques maintaining the soil under controlled laboratory conditions for a period of time (Hadas et al., 1989) and the results obtained used to feed simulation models (Gilmour and Gilmour, 1980). It is argued; however, that laboratory studies may lead to results being overestimated with respect to natural field conditions as soil moisture and temperature are variable and often suboptimum (Gilmour and Gilmour, 1980). Robinson (1957) investigated the mineralisation of nitrogen at various soil moisture contents from permanent wilting point to field capacity. The study found that the mineralisation rate was maximised when the soil was at or around field capacity.

In addition, Kruse et al. (2004) demonstrated that nitrogen mineralisation was higher when soil moisture content was constant compared to a fluctuating condition; i.e. repeated wetting and drying. Echeverría and Sainz Rozas (2005) suggested that the optimum temperature for the activity of Nitrosomonas and Nitrobacter is between 25 and 35 degrees Celsius. Bashkar and Charyulu (2005) reported that the optimum soil pH for these types of bacteria is 8. An earlier work undertaken by Tejada et al. (2002) using mineral and organomineral fertilisers obtained the highest net mineralisation when amended soils were incubated at 25 degrees Celsius. Studies with ^{15}N showed that nitrogen availability from nitrogen fertilisers does not reach 100% (Recous, 2001). This is attributable to a ‘substitution effect’ as proposed by Hart et al. (1986) whereby a proportion of the nitrogen in the fertiliser applied becomes immobilised instead of the natural soil nitrogen. Immobilisation is a temporary process by which microorganisms compete for nitrogen with the growing crop (Echeverría and Sainz-Rozas, 2005). In the longer term, microorganisms’ decay replenishes the soil with mineralisable nitrogen (Recous, 2001) which can potentially be recovered in the following crop (López et al., 2002).

Immobilisation of fertiliser-N has also been reported to take place in situations where there are high organic residues on the soil surface such as in conservation tillage or forage systems (Doran, 1980; Janson and Person, 1982). It may be enhanced under the latter conditions because of the larger microbial populations (Rice and Smith, 1984) and organic residues which provide a high C:N ratio at the soil surface (Kitur et al., 1984; Espinosa et al., 1985).

2.6.7 Nitrogen uptake by crops

Detailed literature on the subject of nitrogen uptake and assimilation includes the work of Engels and Marschner (1995) and Forde and Clarkson (1999) among others. Inorganic nitrogen is mainly transported to plant roots in mass flow (Cooke, 1982; Darwich, 1998; Tognetti et al., 2005; Kirkby et al., 2009) as highlighted earlier. A recent study demonstrated that nitrogen concentration in wheat was positively correlated with water availability in the soil (Melaj et al., 2003). The uptake of mineral nitrogen by crops is controlled by a number of factors including chemical and spatial availability in the soil, transport systems in the plasma membrane of root cells, the architecture of the root system, and metabolic mechanisms in the root involved in the transport and assimilation of nitrogen (Jackson et al., 2008; Kirkby et al., 2009). Most importantly, nitrogen uptake is regulated by crop demand which is determined by shoot-root interactions in which nitrate acts as a signal for metabolism and root development (Kirkby et al., 2009). The implication is that root tips, especially lateral roots, would convert the nitrate signal into root growth responses (Forde, 2002).

However, Robinson (1996) questioned the effect of nitrate on root expansion on the basis of the high mobility of nitrate in the soil. Nitrogen can be taken up by crops either as ammonium or nitrate (Mengel and Kirkby, 1987). Recently, soluble organic nitrogen has received increasing attention as an alternative source of nitrogen available for uptake by crops (Kirkby et al., 2009). Soluble organic nitrogen may be taken up by crops as amino compounds as proposed by Näsholm et al. (2009). In addition, Walch-Liu et al. (2006) stated that plant roots are able to respond to changes in the concentration of glutamate which is a component of dissolved soil organic nitrogen. For most arable soils, the ratio of nitrate to ammonium is approximately 10-20:1 (Miller et al., 2007). Nitrate has to be reduced to ammonium prior to being incorporated into organic compounds; namely, amino acids in the chloroplasts (Kirkby et al., 2009). Therefore, from the energy point of view, absorption of ammonium may be an advantage for the plant. The effect of the nitrogen source upon crop growth and agronomic performance depends on a number of factors including soil type, the interaction between the soil and the nitrogen source, and crop type and variety. The rate of nitrate and ammonium uptake is also influenced by soil pH. Under more acidic conditions ($pH<7$) nitrate uptake is increased whereas ammonium uptake is higher with soil pH closer to neutrality or higher than 7 (Echeverría and Sainz Rozas, 2005). Relatively high absorption of ammonium can compromise the uptake of calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^{+}), and vice-versa with increased nitrate uptake (Kirkby and Mengel, 1967; Kirkby, 1968).

Similarly, the uptake of ammonium promotes the uptake of anions in order for the plant to maintain the neutrality in the membranes (Kirkby et al., 2009). Changes in pH in the rhizosphere are induced by the form of nitrogen uptake (Römheld, 1986). The root uptake of nitrate is associated with the influx of H^+ in the ratio of $2H^+$ per NO_3^-; therefore, H^+ is removed from the rhizosphere increasing soil pH (Kirkby et al., 2009). The uptake of the three main cations is consequently enhanced by nitrate uptake in order for the plant to maintain the charge balance (Kirkby et al., 2009). Echeverría and Sainz Rozas (2005) suggested that the root uptake of nitrate and ammonium results respectively in the release of HCO_3^- and H^+. These ions, in turn, can cause either an increase or decrease of soil pH in the rhizosphere thereby favouring the differential uptake of one of the two nitrogen forms.

Similarly, the changes in pH in the rhizosphere induced by the particular form of nitrogen uptake affect the uptake of other soil nutrients (Kirkby et al., 2009) including micronutrients. Nitrate assimilation is affected by molybdenum supply (Mengel and Kirkby, 1987) whose availability to crops increases with soil pH (Donahue et al., 1981). Molybdenum is needed for the electron transfer during the reduction of nitrate to nitrite (Guerrero et al., 1981). In addition, nitrate reductase activity; i.e. the enzyme involved in the reduction of nitrate, can affect crop yield as it regulates nitrate assimilation rate (Mengel and Kirkby, 1987). Eilrich and Hageman (1973) indicated that the activity of the enzyme in the flag leaf of wheat depends on the nitrate supply. Increased enzymatic activity in flag leaf was also linked to increased nitrogen content in grain. Croy and Hageman (1970) suggested, however, that nitrogen content in grain was better explained by the translocation rate of amino compounds from the leaves on to the grains. The effect of nitrogen uptake in cereal crops is that it promotes shoot growth by increasing both the number of tillers on the plant and the number and size of the leaves and internodes on each tiller as a result of the increase in the number and mean volume of cells (Milford and Johnston, 2007). Hence, the growth and development of the leaf canopy requires significant uptake of nitrogen into the shoot. This nitrogen uptake is supplemented by large uptakes of potassium which is needed to maintain osmotic potentials and turgor in new generated cells and tissues (Milford and Johnston, 2007). When potassium supply to the crop is not restricted, nitrogen and potassium uptake are dependent on nitrogen supply (Milford and Johnston, 2007). An ongoing, yet unpublished, work reported by Kirkby et al. (2009) and being undertaken at the Chinese Agricultural University in Beijing in which maize plants received localised supply of ammonium nitrogen.

Preliminary findings of that work showed that there was an abundant root formation where ammonium was placed. This root development was associated with a significant decrease in pH in the rhizosphere (from 7.8 to 5.0), which was responsible for increased solubility and uptake of soil phosphorus.

2.6.8 Nitrogen fertilisation

The application of nitrogen fertiliser to crops is aimed at filling the gap between crop nitrogen requirement for a targeted crop yield and the soil nitrogen supply (Olfs, 2009). Whenever possible, other nitrogen inputs or losses, such as atmospheric deposition and fixation or leaching, should be accounted for when making a nitrogen fertiliser recommendation (Olfs, 2009). Soil nitrogen supply (SNS) includes three components; soil mineral nitrogen; i.e. nitrate-N plus ammonium-N, total crop nitrogen and mineralisable soil nitrogen during the crop growing season (MAFF, 2000). Nitrogen fertiliser recommendations are based on the SNS Index System described in MAFF (2000). This includes two methods; namely, the Field Assessment and the Soil Mineral Nitrogen (SMN) Analysis Methods (MAFF, 2000). The choice of a particular method largely depends on specific conditions; e.g. previous crop, soil type, soil fertility status and rainfall area among others. In both methods, an SNS index is calculated which is used to estimate the nitrogen application rate given according to the crop and soil type. In most circumstances, nitrogen is not applied to the seedbed in cereal crops sown in the autumn. Application of nitrogen to winter wheat in the spring may be performed as follow depending on the total nitrogen rate to be applied. The recommendations for the application of nitrogen to winter wheat given in RB209 (MAFF, 2000) are quoted below:

- Nitrogen rates **≤120 kg [N] ha^{-1}**; the whole amount is applied as a single dressing in early stem extension; i.e. growth stage 30-31 (Tottman and Broad, 1987), but not before early April.
- Nitrogen rates **≥120 kg [N] ha^{-1}**; split into two dressings as follow:
  - Approximately 40 kg [N] ha^{-1} between mid-February to mid-March; i.e. growth stages corresponding to tillering, especially when the number of shoots are low as well tillered crops can result in lodging later in the season.
  - Apply the balance in one or two dressings during early stem extension; i.e. growth stage 30-31 (Tottman and Broad, 1987). If the balance is ≥120 kg [N] ha^{-1}; then split into two applications of 50% of the amount each. This should be done at stages 30-31; i.e. at the start of stem extension but not before early April, and at stage 32; i.e. approximately two weeks later but not after early May.

- For **bread-making varieties** up to 40 kg [N] ha^{-1} may also be applied to increase the nitrogen content in grain for a 2.2% [N] (w w^{-1}) target as follow:
  - Liquid nitrogen; e.g. foliar urea or UAN, at growth stage 71-75; i.e. milk development (Tottman and Broad, 1987) approximately early July, or
  - Solid nitrogen at growth stage 37; i.e. flag leaf visible (Tottman and Broad, 1987) approximately late May/early June. This will also have an effect on grain yield.

The content of nitrogen in grain is an important quality parameter (Johnston and Poulton, 2009). The target for feed wheat varieties is 2% [N] (w w^{-1}) content and should be adjusted by increasing/decreasing the nitrogen application rate by 30 kg [N] ha^{-1} for each 0.1% [N] (w w^{-1}) content in grain below/above the target respectively (MAFF, 2000). The protein content in grain is estimated by multiplying the total nitrogen content in the grain by a nitrogen to protein conversion factor which is obtained from the aminoacids composition of the grain (Mossé, 1990). It is generally accepted a standard factor of 5.7 as proposed by Teller (1932). Miflin (1978) suggested that the production of cereal crops with high nitrogen content in grain and high grain yield is mainly affected by nitrogen availability from both soil and fertiliser, and the translocation of nitrogen from the plant to grains. Nitrogen content in grain was shown to increase almost linearly for increasing nitrogen application rates in the range of 48-288 kg [N] ha^{-1} (Benzian and Lane, 1979 & 1981; Johnston and Poulton, 2009).

Dilution effects can occur when there is a rapid increase in grain yield after adding a small amount of nitrogen fertiliser; e.g. from zero to 50 kg [N] ha^{-1}, and as a result there is a reduction in the concentration of nitrogen in grain compared to the crop grown in the absence of nitrogen application (Benzian and Lane, 1979 & 1981; Johnston and Poulton, 2009). Results from the Broadbalk Experiment at Rothamsted between 1996 and 2000 showed that maximum grain yields equivalent to 8.3-9.3 t [grain] ha^{-1} and nitrogen contents in grain of 1.93-2.13% [N] (w w^{-1}) for winter wheat *cv.* Hereward were achieved when nitrogen was applied in the range of 192-240 kg [N] ha^{-1} (Rothamsted Research, 2006; Johnston and Poulton, 2009). The methods proposed by MAFF (2000) have recently been questioned on the basis that experimental evidence suggests that they could lead to nitrogen recommendations being sub-optimum under continuous arable cropping conditions (Orson, 2009). A recent review of experimental data conducted by Rothamsted Research and TAG (The Arable Group) to identify optimum levels of nitrogen fertilisation in winter wheat for the period 1997-2006 suggested that there was not a clear relationship between SMN measured in February and MERN (Knight et al., 2008; Orson, 2009).

For the 30 TAG trials, the best approach appeared to be the application of 240 kg [N] ha^{-1} in spite of the previous crop, soil type or SMN supply (Orson, 2009). The standard farm practice for winter wheat in continuous arable rotation involves nitrogen application rates in the range of 180-220 kg [N] ha^{-1} but these are very depending on specific site conditions and nitrogen fertiliser price. These levels of nitrogen fertilisation are in close agreement with those recorded for winter wheat at the College Farm at Silsoe for the harvest seasons 2006-10 on sandy loam soils (range 200-227 kg [N] ha^{-1} for a grain yield range of 8.90-9.30 t [grain] ha^{-1}; O'Dell [2010]). Jenkinson (1982) reported that for the period 1852-1967, the apparent fertiliser nitrogen recovery value (grain and straw excluding roots) at Rothamsted for the Continuous Wheat Experiment was 32% for the treatment receiving 144 kg [N] ha^{-1} per year. More recently, as a result of the use of higher yielding varieties, this value was found to increase to 86%.

MAFF (2000) uses a value of nitrogen fertiliser recovery in grain of 70% with the remaining 30% being recovered in the straw and returned to the soil. The application of nitrogen to grass follows a similar approach to that given for arable crops in MAFF (2000). Firstly, a SNS status; i.e. high, moderate or low, is determined based on typical nitrogen use in the past 2-3 years and the management of the grass in the previous year. Secondly, a grass growth class is identified; i.e. high, medium or low, based on the soil type and the mean summer rainfall. Finally, a recommendation is made for the intended grass management based on the SNS status and adjusted by the grass growth class previously determined. Recommendations in MAFF (2000) provide the maximum nitrogen rate for intensively stocked fields of average to very poor grass growth classes. For those classified as good or very good, the nitrogen application rate may be increased by 40 or 80 kg [N] ha^{-1} respectively throughout the growing season.

In addition, the SNS status needs to be adjusted when organic manures have been frequently used or when grass is used for silage receiving low nitrogen inputs in the form of manures; i.e. increase or decrease SNS accordingly. The first application of nitrogen to grass is normally performed between late February and mid-March depending on the air and soil temperatures and ground conditions since the growth of the grass is induced when soil temperature is consistently at/above 6 degrees Celsius (Morrison et al., 1980; Frame, 1992; Fisher and Jewkes, 2009). The T-sum 200 method has been used to identify the date for the first nitrogen application to grass. This method is based on the cumulative maximum air temperatures after 1st January to reach 200 degrees Celsius (Fisher and Jewkes, 2009).

Despite its relative success in the UK, it is recognised that between 2 to 5 weeks around this point fertiliser nitrogen application approaches the optimal with up to 90% of the nitrogen applied being used for growth (Fisher and Jewkes, 2009). The application of nitrogen to grass is usually split to provide approximately 50-60 kg [N] per month throughout the growing season but this is largely dependent on the grazing and cutting regimes and the SNS status (MAFF, 2000). Application of nitrogen to grass later than mid-August may be omitted in dry years. Annual yields of rye grass receiving zero nitrogen, 150 and 300 kg [N] ha^{-1} per year were found to be 1.98, 5.79, and 8.72 t [DM] ha^{-1} per year respectively measured at over 20 experimental sites in England and Wales over a period of 4 years (Morrison et al., 1980). The same work reported values of nitrogen content in harvested grass throughout the growing season in the range of 1.73-2.46, 1.90-2.95, and 2.37-3.45 %N (w w^{-1}) for applications of zero, 150 and 300 kg [N] ha^{-1} per year respectively.

The nitrogen content in harvested plant material, thus, crude protein content, is related to the nutritional value of the grass. Crude protein can be estimated by multiplying the total nitrogen content (Kjeldalh’s nitrogen) of harvested plant material by 6.25 (Raymond, 1959). Nitrogen content is also related to the digestibility of the material; i.e. the percentage of organic matter in the grass eaten which is not excreted, and a graphical relationship between the two parameters was produced by Raymond (1959). Morrison et al. (1980) encountered apparent recovery values of nitrogen fertiliser in harvested plant material of 64% and 70% when nitrogen was applied to rye grass at rates of 150 and 300 kg [N] ha^{-1} per year respectively.

2.6.9 Nitrogen leaching

Nitrate from farmland constitute one of the most important source of nitrate in waters in Western Europe (Defra, 2009d). In England, up to 70% of the nitrate input to surface and subsurface waters comes from agricultural land (Defra, 2009d). Losses of nitrogen and phosphorus from agriculture are recognised as being major contributors to diffuse pollution in waters (ADAS, 2009; Defra, 2009d). Addiscott et al. (1991) observed that one of the reasons for the increment in nitrate concentration in waters following the Second World War was the associated increase in the use of nitrogen fertilisers. WHO (1985) acknowledged that nitrate in drinking waters poses a health hazard and the EU under the Nitrate Directive 91/676/EC and the Drinking Water Directive 80/778/EC imposed a limit of 50 mg [NO_3^-] l^{-1} for drinking waters (CEC, 1980 & 1991). This value is commonly surpassed in potable waters obtained from surface and groundwater fed by waters from agricultural areas (Kirchmann et al., 2002).

Although nitrate has relatively low toxicity in adults (Hill, 1991) chronic toxic effects may result from nitrite formation by bacteria (Hill, 1999). Infant methaemoglobinaemia is associated with intake by babies of nitrate rich drinking water (Comly, 1945; Hill, 1999). When haemoglobin, the substance responsible for the transport of oxygen in the body, reacts with nitrite produces methaemoglobin which has large reduced oxygen carrying capacity so that infant tissues are oxygen deficient resulting in cyanosis (Hill, 1999).

Nitrogen and phosphorus enrichment of water courses is known to be the main cause of eutrophication (Collins, 1996). This phenomenon is caused by excessive development, followed by death, of algae which undergo bacterial decomposition depleting the oxygen from the water. This, in turn, causes the death of other living organisms (Addiscott et al., 1991). An important aspect in dealing with eutrophication is to know where the nitrogen and phosphorus entering the waters originate, the rate at which they enter and their fate in the water course (Collins, 1996). Nitrogen leaching occurs mainly in the form of nitrate (Minderman and Leeflang, 1968; Amberger, 1983). However, losses of ammonium-N and urea-N were reported (Macdonald et al., 2006) and some of their findings are reviewed below. Losses of ammonium-N following application of urea and ammonium nitrate were found to be above the limits (0.04-1.0 mg [NH_4^+] l^{-1}) imposed under the Freshwater Fish Directive 78/659/EC (CEC, 1978). Nitrate is negatively charged and cannot be strongly adsorbed to soil particles in the range of soil pH commonly found in temperate agricultural soils (Addiscott et al., 1991). Hence, nitrate remains in solution and it is prone to being lost from the soil-root system by leaching.

Under acidic soil conditions; e.g. tropical soils with pH<5 and clay particles being more positively charged, nitrate may be retained more strongly against leaching (Wong et al., 1987).
On the other hand, ammonium is held more tightly to clay particles charged negatively reducing the scope for leaching. Leaching takes place when soil water exceeds the maximum water holding capacity of the soil and nitrate present in the soil solution moves downwards to a point where it cannot longer be taken up by plant roots (Amberger, 1983; Russell, 1988). At this point nitrate is lost from the soil-root system. In drier soil conditions, and within certain limits, nitrate can move upwards together with soil water ascending by capillary action (Mengel and Kirkby, 1987). When water enters the soil and moves through natural cracks and channels nitrate leaching may be reduced if that water does not interact with existing soil-water containing nitrate in solution; for example, water held in fine pores inside soil aggregates (Beven, 1981, Addiscott et al., 1991; Echeverria and Sainz-Rozas, 2005).

However, nitrate leaching may be enhanced by means of a by-pass flow if fertiliser application was practiced immediately before a rainfall event and nitrogen fertiliser was carried in the water through channels and large pores (Addiscott et al., 1991). This mechanism of nitrogen transport through preferential pass flow was reported to be important in some clay soils (Smaling and Bouma, 1992; Gooday et al., 2007). In addition, nitrate in water trapped inside soil aggregates can move out by means of diffusion to water between aggregates; i.e. following a gradient of concentration between the two points. This can provide the opportunity for nitrate to be lost if water in larger pores; i.e. between soil aggregates, subsequently moves downwards by gravity carrying with it the nitrate in solution (Addiscott et al., 1991). Bowden (1996) identified two main factors controlling nitrate leaching; **i.** concentration of nitrate in the soil solution, which is related to the mineralization rate of soil organic nitrogen, and the nitrogen fertiliser input; and **ii.** the effect of rainfall and the rate of water movement through the soil profile. The latter is largely influenced by soil type and the conditions affecting soil water movement. In this respect, Amberger (1983) highlighted the importance of soil texture and soil organic matter, and Low and Armitage (1970) demonstrated the effect of soil use and management on nitrate leaching. This study compared the effect of different soil uses on nitrogen loss by leaching and reported values of *c.*100 and *c.*4 kg [N] ha^{-1} per year for fallow land and grass respectively.

A recent study (Meisinger et al., 2006) estimated nitrate losses by leaching to be between 10% and 30% of the total nitrogen applied in most agricultural systems. In cereal crops, net mineralisation usually takes place after the senescence of the flag leaf and increases with tillage operations conducted after the harvest (Meisinger et al., 2006). This means that nitrate can accumulate in post-harvest of the crop providing an opportunity for nitrate leaching during the autumn and winter periods. Nitrate leaching during the winter may be aggravated if it was preceded by a dry autumn (Garwood and Tyson, 1973). In grassland soils, as the grass crop remains active for longer into the autumn-winter, losses of nitrate by leaching are expected to be lower compared with that from arable land (Russell, 1988). The inclusion of deep rooted crops in the rotation can help to mitigate nitrogen leaching by recovering a proportion of the nitrate that was transported beyond the root zone in previous crops (Kristensen and Thorup-Kristensen, 2004). Studies with ^{15}N in winter wheat (Macdonald et al., 1989) indicated that 17% (range 7-36%) of the total nitrogen applied to the crop in the spring (range 47-234 kg [N] ha^{-1}) persisted at harvest but only a small amount (1.3%, range 0.4-3.6%) was found to be mineral nitrogen. On the contrary, *c.*89% of the soil mineral nitrogen at harvest was unlabelled suggesting that this nitrogen was originated from mineralisation of soil organic nitrogen instead of residual nitrogen from the fertiliser.

Further, the study indicated that unfertilised crop was found to have a similar level of soil mineral nitrogen to the crop that received 234 kg [N] ha^{-1} in the spring. These results suggest that the risk of nitrate leaching in autumn and winter is mainly derived from inorganic nitrogen originated from mineralisation of soil organic nitrogen and not necessarily from residual nitrogen fertiliser not taken up by the crop. Macdonald et al. (1989) also indicated that there would not be a significant benefit in reducing the amount of nitrogen fertiliser use to prevent nitrate leaching from occurring in post-harvest. The use of controlled release fertilisers may be recommended in certain areas of high rainfall and permeable soils to reduce nitrogen losses by leaching (Mengel and Kirkby, 1987). One of the disadvantages in the use of this type of fertilisers is due to the complex mechanisms controlling the release of nutrients from the fertiliser which can result in crop nutrients' requirements being mismatched by the nutrients becoming progressively available (Miner et al., 1978; Mengel and Kirkby, 1987; Wilson, 1988).

There are a number of techniques to measure nitrate losses from the soil and a full description of them is given by Addiscott et al. (1991). These include the use of porous ceramic caps which extract the soil solution by suction (Wagner, 1962), collection and analysis of water-flows from field drainage systems (Barraclough et al., 1983), and lysimeters. Lysimeters have long been used for the study of the fate and behaviour of contaminants in the soil-plant-groundwater system, water and solutes fluxes in the soil, and soil nutrient balances and leaching (Gerzabek, 2008). In most cases, a lysimeter consists of a cylindrical or square section container filled with soil and a device to collect and quantify the leachate (Meiβner et al., 2008).

2.6.10 Gaseous losses of nitrogen

This section provides a brief review of two important processes for nitrogen losses which include nitrous oxide (N_2O) emissions and volatilisation of ammonia (NH_3).

i. Nitrous oxide (N_2O)

There are three main gases related with greenhouse gas emissions from agricultures: CO_2 (carbon dioxide), CH_4 (methane) and N_2O (nitrous oxide) (Snyder et al., 2007). These three gases differ markedly in their efficiency at absorbing infrared radiation (Snyder et al., 2007). Estimates suggest that the global warming potential (GWP) of N_2O is approximately 296 times higher than that of CO_2 (Snyder et al., 2007) although IPCC (1996) uses an equivalent value of 310. N_2O is one of the greenhouse gases that require inventories under the Kyoto Protocol of 1997 (Smith and Dobbie, 2001).

Nitrogen fertilisers (including organic-based materials) are considered to be one of the main contributors to N_2O emissions (Smith and Dobbie, 2001). Smith et al. (2006) stated that N_2O contributes approximately 6% of the GWP of all UK greenhouse gas emissions. The same work indicated that agriculture is responsible for *c*.67% of UK N_2O emissions and it is also highlighted that the use of N-fertilisers in the UK agriculture are responsible for *c*.2% of the total greenhouse gas emissions.

A common method to measure N_2O emissions involves the use of the static chamber technique described in Thorman et al. (2007). Nitrous oxide emissions are produced by the microbial processes of nitrification and denitrification (Bange, 2000; Echeverría and Sainz-Rozas, 2005). There are a number of factors controlling the formation of N_2O; Snyder et al. (2007) indicated that temperature determines the rate at which microorganisms nitrify/denitrify; it tends to decrease at lower temperatures. The author also highlighted that the concentration of oxygen in the soil is another important factor influencing these processes and it is linked to the moisture content in the soil. In addition, the concentration of NH_4^+ and NO_3^- in the soil are important as these forms of nitrogen can undergo further transformations (nitrification and denitrification, respectively) resulting in the formation of N_2O (Snyder et al., 2007). Based on Granli and Bøckman (1994), specific microorganisms can obtain energy by using NO_3^- for oxidation of inorganic compounds such as S^{2-} and Fe^{2+} during autotrophic denitrification. In addition, heterotrophic denitrification is usually a more important process in the formation of N_2O; this process as described by Granli and Bøckman (1994) is shown below:

$$NO_3^- \to NO_2^- \to NO \to N_2O \xrightarrow{N_2O\ reductase} N_2$$

Granli and Bøckman (1994) highlighted that heterotrophic denitrification needs both anaerobic conditions and the presence of a substrate that can be used by bacteria. In addition to the denitrification processes, N_2O can also be produced during nitrification; based on Groffman (1991) and Granli and Bøckman (1994), it occurs at intermediate stages between NH_4^+ and NO_2^-; also NO_2^- can decompose itself to result in N_2O, particularly under more acidic conditions (chemodenitrification). Smith et al. (2006) highlighted that in addition to the direct sources of N_2O there are indirect sources which include for example N that was deposited on the ground following ammonia volatilisation and in addition to that, nitrate leaching from farmland in drainage waters.

Reviews on the subject include the work of Granli and Bøckman (1994), Mosier et al. (1998), Bouwman et al. (2002a-b). Smith et al. (2006) also indicated that IPCC suggested using a default value for the N_2O emission factor for its use in direct emissions from agricultural soils of 1.25% of the nitrogen applied as fertilisers; including both organic-based materials and mineral fertilisers and also N contained in ploughed in crop residues (IPCC, 1997; Mosier et al., 1998).

ii. Volatilisation

The UK Government has committed to reduce ammonia emissions to below 297 kt [NH_3] per year by 2010 under the EU National Emission Ceilings Directive 2001/81/EC (CEC, 2001) and the UNECE (UN Economic Commission for Europe) Gothenburg Protocol of 1st December 1999 (CEC, 2001; Chambers and Dampney, 2009). The Ammonia Emissions Inventory 2007 from Agriculture (Misselbrook et al., 2008) reported that *c*.40 kt [NH_3] per year, equivalent to *c*.16% of all agricultural emissions, are originated from the spreading of manufactured nitrogen fertilisers, especially, urea-based fertilisers (Chambers and Dampney, 2009). Recent investigations into ammonia emissions from manufactured nitrogen fertilisers include the work undertaken under the Defra NT26 Project coordinated by ADAS (Chambers and Dampney, 2009). This work assessed the suitability of alternative nitrogen fertiliser sources to ammonium nitrate in an attempt to address security related issues at national level. The research investigated urea as a potential fertiliser source to replace ammonium nitrate and significant amount of the work was devoted to ammonia emissions under the project work package WP1b reported in Chadwick et al. (2005). Ammonia emissions can be measured in-field conditions using wind tunnels as proposed by Lockyer (1984). The application of urea to the soil produces its hydrolysis resulting in the formation of ammonium carbonate (**Equation 2.7**). This compound is very unstable and it can quickly undergo further transformations (**Equations 2.8**) resulting in the formation of gases ammonia (NH_3) and CO_2 (Sengik et al., 2001) as shown in **Figure 2.7** below. The hydrolysis also induces a temporary increase in soil pH to *c*. 9.0 in the proximity of the fertiliser particle (Overrein and Moe, 1967; Echeverría and Sainz Rozas, 2005). This increase in the soil pH at the site of hydrolysis enhances the emission of ammonia (NH_3) to the atmosphere (Darwich, 1998).

$$CO(NH_2)_2 + 2H_2O \xrightarrow{Urease} (NH_4)_2CO_3 \qquad \textbf{[2.7]}$$

$$(NH_4)_2CO_3 \longrightarrow 2NH_3\uparrow + CO_2\uparrow + H_2O \qquad \textbf{[2.8]}$$

Figure 2.7: Hydrolysis of urea and formation and subsequent emission of ammonia to the atmosphere (from Sengik et al., 2001).

As shown in **Figure 2.7**, the process of hydrolysis is governed by the activity of urease which is an enzyme that occurs naturally in the soil (Echeverria and Sainz-Rozas, 2005). The urease activity is highly influenced by soil temperature (Moyo et al., 1989). Linear relationships were found between the increase in soil temperature (range 2-45 °C) and urease activity (Gould et al., 1973) and between soil temperature (range 10-30 °C) and ammonia volatilisation (Sainz-Rozas et al., 1997) following application of urea to the soil.

The volatilisation of ammonia following surface application of urea to the soil is also affected by the rate of urea-N used. Overrein and Moe (1967) found that volatilisation increased exponentially as a function of the rate of urea used. However, the effect of urea-N rate on ammonia volatilisation was also shown to be dependent on the crop type. Chambers and Dampney (2009) obtained significant linear relationships between the application rate of urea-N and the amount of nitrogen lost in the form of ammonia, as percentage of the total nitrogen applied, when urea was applied to grass. However, this significant effect could not be demonstrated when urea was applied to winter wheat. In addition, ammonia emissions are affected by the occurrence of rainfall immediately after application. Small amounts of rainfall; e.g. 15 mm, can contribute to reduce losses compared with prolonged dry periods post-application (Chambers and Dampney, 2009).

Volatilisation is enhanced in moist soils experiencing high evaporation rates; e.g. air temperature above 20°C and windy conditions, and also when soil pH is above 8 (Darwich, 1998). Measures to mitigate losses of nitrogen by volatilisation include soil incorporation of urea during/following application (Darwich, 1998). Overrein and Moe (1967) demonstrated that the rate of ammonia volatilisation was inversely proportional to the depth to which urea was incorporated. Chambers and Dampney (2009) reported ammonia emission factors; i.e. NH_3-N loss as percentage of total nitrogen applied, from granular urea of 27% (range 10-58%) for grass and 22% (range 2-43%) for winter cereal crops whereas for ammonium nitrate the emission factor was found to be *c*. 3% for both crop types. The same work reported that in order to obtain the same level of crop yield an additional 20% of urea-N would be required to obtain the same level of grain yield and quality in cereal crops as from the application of ammonium nitrate.
In addition, for a nitrogen application rate equivalent to 220 kg [N] ha^{-1} a grain yield reduction of *c*.0.3 t ha^{-1} was obtained when urea was used instead of ammonium nitrate.

Losses of nitrogen in the form of volatile NH_3 from the plant after fertiliser application and during the senescence period were reported by Harper et al. (1987). The work indicated that prior to anthesis, atmospheric NH_3 absorption was observed during a period when soil-N was temporarily unavailable. Approximately 21% equivalent of the applied fertiliser was reported as lost by volatilisation of NH_3. When soil-N was unavailable for plant uptake, up to 1% equivalent of the applied fertiliser was gained from atmospheric NH_3 by plant absorption.

2.6.11 Nitrogen use efficiency (NUE)

There are several indices and methods to determine the efficiency at which plant nutrients are used in crop production. Johnston and Poulton (2009) based upon the work of Cassman et al. (1998) provided a description of these methods which are summarised below (after Johnston and Poulton, 2009):

- **Direct method:** this method consists of the use of ^{15}N and the labelling of N-fertiliser with this isotope which allows measuring the N from the fertiliser in the growing crop, the harvested product and also the residual nitrogen remaining in the soil at harvest. The results are usually expressed in percentage. It generally acknowledged that they can provide accurate estimates of nitrogen use efficiency; however, the main disadvantage of ^{15}N experiments is the cost associated with their use.
- **Difference method:** this method requires that the treatments in the same experiment have and have not been applied with nitrogen fertiliser. The data can then be used in two ways, as follow:

    - **NUE using crop yield**; this method is usually regarded as the 'agronomic efficiency' (A_E) of applied nitrogen fertiliser: $A_E = \frac{(Y_N - Y_{N=0})}{N_{Rate}}$ where: Y_N and $Y_{N=0}$ are the yields of the crop (kg [grain] ha^{-1}) corresponding to the treatment ($N \neq 0$) and the control ($N=0$) respectively, and N_{Rate} is the nitrogen application rate (kg [N] ha^{-1}).

    - **NUE using nitrogen uptake**; this method is often regarded as the 'apparent recovery' (R_N) of applied nitrogen: $R_N = \frac{(U_N - U_{N=0})}{N_{Rate}}$ where: U_N and $U_{N=0}$ are the nitrogen uptake by the crop (kg [N] ha^{-1}) corresponding to the treatment ($N \neq 0$) and the control ($N=0$) respectively, and N_{Rate} is the nitrogen application rate (kg [N] ha^{-1}).

Estimations of absolute recovery of nitrogen in the fertiliser, although possible, are more difficult to make. They require measurement of nitrogen accumulated in roots, stubble and soil organic matter as well as nitrogen lost by leaching or other mechanisms (Morrison et al., 1980). In addition to the indexes listed above, there are two other indicators of nitrogen use efficiency frequently used; the partial factor productivity of applied nitrogen and the physiological efficiency of applied nitrogen. These are shown below (after: Johnston and Poulton, 2009):

- **Partial factor productivity of applied nitrogen (I_P):** this index is calculated as the ratio between the kg of product obtained per kg N applied; therefore, $I_P = \frac{Y_N}{N_{Rate}}$ where Y_N and N_{Rate} are defined as above.
- **Physiological efficiency of applied nitrogen (P_E):** it is defined as the kg of product increase per kg increase in nitrogen in the crop; therefore, $P_E = \frac{(Y_N - Y_{N=0})}{(U_N - U_{N=0})}$ where: Y_N, $Y_{N=0}$, U_N and $U_{N=0}$ are defined as above.

2.6.12 Phosphorus

This section presents a brief overview of the phosphorus cycle based upon the review conducted by Johnston and Syers (2006) where the concepts summarised herein can be found. It provided an insight into the behaviour of soil phosphorus, especially, with regards to soil available-P. The authors stated that the availability of P in the soil can be explained by concepts relating to ‘P equilibria in soils’ which involves adsorption and desorption reactions; these are understood to be reversible with time (Johnston and Syers, 2006). A simplified representation of the phosphorus cycle is presented in **Figure 2.8** (after: Johnston and Syers, 2006).

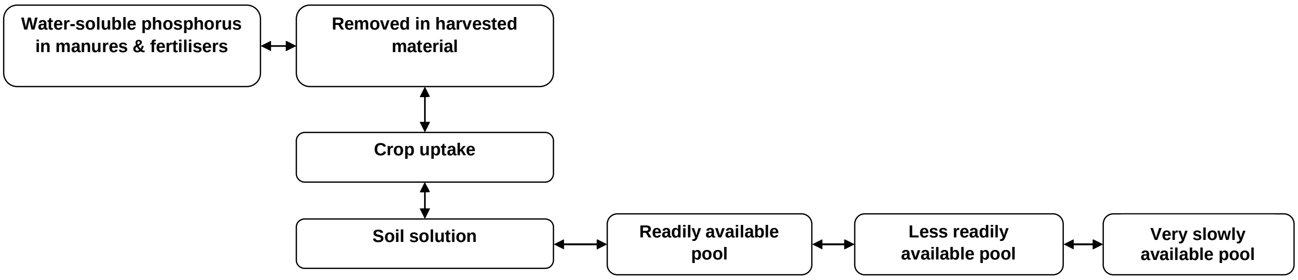


Figure 2.8: Simplified representation of the phosphorus cycle (after: Johnston and Syers, 2006).

Johnston and Syers (2006) proposed that this concept of reversible P replace the earlier one which suggested that applied P (water-soluble P) to the soil could be irreversibly fixed thereby becoming unavailable for plant uptake, and emphasised that this latter view must be discarded. The authors indicated that this concept contributed to developing the idea of applying P to ensure that a critical level in the soil was maintained; this being in relation to the soil type and the particular production system. According to the authors, soil-P is retained by a continuum of bonding energies and they suggested that the amount of phosphorus extracted in soil analyses can be related to the response of the crop to the application of P-fertilisers. The diagram shown in **Figure 2.8** indicates that phosphorus is in various pools in the soil which differ on the extent to which soil-P is available for plant uptake. The phosphorus located in the soil solution is totally available for the use by the crop; a second pool (readily available pool) considers P retained on the surface sites and it can be easily extracted in standard soil analysis (Johnston and Syers, 2006). The importance of this phosphorus fraction is that it is in constant equilibrium with that of the soil solution.

The concentration of P in the soil solution is largely driven by plant uptake; hence, its replenishment depends upon the phosphorus held at surface sites. The authors proposed that a third pool contains phosphorus more strongly held to soil constituents (less readily available pool) and also phosphorus adsorbed on internal surfaces in the soil matrix. This fraction, however, can slowly become available for plant uptake. Finally, a fourth pool which contains very slowly available phosphorus; this can require several years to be released and become available and it includes P- strongly held to soil constituents, P that may be part of the mineral soil components or P that has undergone precipitation (Johnston and Syers, 2006). Standard soil analyses such as Olsen-P (Olsen et al., 1954) for determination of soil-P generally extract that contained in the soil solution and the readily available P fraction and it is equivalent to the plant available P. The authors emphasised that an important aspect of concept proposed (**Figure 2.8**) is the reversibility of the phosphorus between the pools (excluding the very slowly available pool). This concept replaces earlier ideas that phosphorus (applied water soluble-P could be irreversibly fixed following application).

Johnston and Syers (2006) indicated that the importance of this idea of the phosphorus pools is that; given the fact that the soil solution and the less readily available pools would provide the majority of the phosphorus to the crop, then it is necessary that a critical level is maintained which led the authors to the concept of the critical level. This level will be in accordance with the soil type and the production/farming system.

The critical level of soil-P was determined by Johnston (2005) in sugar beet crops and it corresponded to the level of soil Olsen's-P at which the yield response of the crop becomes asymptotic. Below this level, there would be a chance for financial losses as a result of the loss of crop yield. Above this level, there is no benefit in terms of crop yield and hence it results in increased fertiliser costs to the farmer in addition to increased environmental risk.

Below are the proposed phosphorus application rates as recommended in RB209 (MAFF, 2000) which are given in relation to the demand by the crop (assuming in winter wheat a grain yield of 8 t ha^{-1}) and the soil-P index. RB209 recommended that when there is not a long term intention of building up soil-P levels, then the recommendation can potentially be reduced by up to 50 kg [P_2O_5] ha^{-1} or 25 kg [P_2O_5] ha^{-1} at indexes 0 and 1 respectively. The recommendations for the application of P are (after MAFF, 2000):

- Winter wheat – straw incorporated:
    - Index 0: 110 kg [P_2O_5] ha^{-1},
    - Index 1: 85 kg [P_2O_5] ha^{-1},
    - Index 2: 60 kg [P_2O_5] ha^{-1} (maintenance),
    - Index 3: 20 kg [P_2O_5] ha^{-1}, and
    - Index $\geq$4: 0.

These recommendations will be also discussed in Chapter 3 in relation to the formulation of the OMF. The following section provides an overview of some work reported in the literature with the use of OMF and it attempts at identifying whether similar product development to that of this research are being conducted.

2.7 Organomineral fertilisers (OMF)

The purpose of this section is to review earlier work involving the use of organomineral fertilisers and to identify the type of OMF products currently in use. FAO (2007) defined OMF as follows: 'fertilisers obtained through blending or processing one or more organic materials with one or more mineral fertilisers to enhance their nutrient content and fertilising value'. In addition, FAO (2007) highlighted that in this type of fertilisers the mineral components are protected by the binding and absorption of organic components which result in more gradual release of nutrients to the soil and the reduction of nutrient losses to the environment. Organomineral fertilisers are often made with organic industrial by-products; most commonly from industries processing meat, fish, leather, sugar-rich materials such as molasses, fruits and wine, and also oil-seeds (Graziano et al., 2008).

A review of the general requirements in organic-based fertilisers was made by Graziano et al. (2008) who considered aspects of the products related with plant nutrition, products' safety and pricing, processing, availability of raw material, regulatory issues, and required physical properties. Graziano et al. (2008) also highlighted that during the past few years, the EC has made attempts to define a common regulation for organic and organic-based fertilisers. In addition, a proposal for a directive was made in the 1990s but it had no success at country level and could not be taken forward and adopted. The authors mentioned above, insisted that there is a need for specific and consistent regulations to be developed and enforced for organic and organomineral fertilisers products used for crop production.

The physical properties of fertiliser materials greatly influence homogeneity of spreading (Hoffmeister, 1982; Allaire and Parent, 2003) and affect their mechanical strength to withstand pressure during handling, transport and storage, and prevent dust formation and caking (Hoffmeister, 1982; Hofstee and Huisman, 1990; Paré et al., 2010a). In this respect, a comprehensive study was conducted by Paré et al. (2009) who investigated the physico-chemical properties of fifty OMF products made from granulated mixtures of various compost materials and the addition of mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP) and peat to the mixture. In addition, a later study by Paré et al. (2010a) reported the characterisation of the physical properties of OMF made from varying proportions of composted pig slurry and mineral fertilisers such as MAP and DAP.

Paré et al. (2010b) highlighted that the physical properties of OMF made with peat can be significantly improved by substituting it with compost from pig slurry, and that its content should be adjusted in relation to the combined effect that the physical and chemical properties have on the response of the crop.

Experiences in the use of OMF included also the work of Richards et al. (1993) who obtained an OMF by mixing mechanically a conventional (mineral) fertiliser with peat followed by palletising and drying of the mixture. Tejada et al. (2005) produced an OMF with 5:2.2:8.3 (NPK) by mixing peat with a number of mineral fertilisers such as urea, mono-ammonium phosphate and potash in a reactor at high temperature. Buondonno et al. (1997) produced two types of OMF by mixing a mineral fertilizer with buffalo manure and peat soil for application on maize. Hountin and Paul (2002) reported the use of organic-based fertilisers for application in maize and rye grass which were made from composted materials of various sources mixed with inorganic fertilizers.

Similarly, Zebarth et al. (2005), produced a palletised OMF (7:4:4) from composted poultry and manure as a nitrogen source for processing potato production. In addition, the works of Schröder et al. (1993), Kemppainen (1995), Jackson and Smith (1997) and also Zebarth et al. (2005), indicated the use of organic-based fertilisers in an attempt to try and reduce the potential environmental impact associated with the continuous use of mineral fertilisers alone which usually release their nutrients more rapidly.

Tejada et al. (2005), however, highlighted that one of the disadvantages of organic-based fertilisers is the existence of a time-lag between the field application and the nutrients' uptake by crop which increases the risk of applied nutrients being lost to the environment. The use of OMF has also been reported for their application in horticultural crops; e.g. Rainbow (1999) and Bélec et al. (2003). This later work indicated the drying and granulation of raw manure and its subsequent use as a nitrogen source for broccoli production supplemented with mineral fertilisers. The study undertaken by Bélec et al. (2003), in Quebec (Canada), demonstrated that the OMF applied had resulted in a beneficial overwinter effect on the following winter wheat crop. Makinde et al. (2007) produced an OMF from cow-dung generated from abattoir and fortified with inorganic nitrogen fertiliser for use in melon (*Citrullus vulgaris L.*) and a similar product was used to measure the response to its application in maize crops (Makinde, 2007).

Other products include for example the production of nitrogen-containing OMF based on wood waste which is obtained following an oxidation process of aspen wood chips with an ammonium solution (Efanov et al., 2001). The resultant product has been reported to be an effective OMF for use in cereal crops (Efanov et al., 2001). In the UK, Southern Water Ltd commercialises treated biosolids granules (sewage sludge) in one tonne bags for agricultural recycling at a price of £26 per tonne (Spence, 2010) which are produced without the addition of any fertiliser source. WIPO (2009) registered a process in Brazil for producing an organomineral fertiliser made from vinasse, filter cake and boiler ashes as by-products of the sugar and/or alcohol industry and optionally complemented with mineral fertiliser sources. This process comprises the following steps; concentration of vinasse, mixing and dissolving the fertilisers in the concentrated vinasse, mixing and drying the filter cake and ashes, impregnating this dry mixture with the fertiliser mixture and drying followed by granulation of the formulated mixture. The final product is granular and contains nutrients in varying concentration depending upon the amount and proportions of fertiliser and additional components added in the process.

2.8 Conclusions

This literature review provided a broad overview of the issues relating to the production and disposal of biosolids and the need for the water industry to secure the agricultural route which appears to be both environmentally acceptable and economically advantageous compared with alternative more expensive options. The study of nitrogen provided a better understanding of its dynamic in agricultural systems; this was a key requirement prior to conducting the work reported in later chapters. Finally, a brief overview of the phosphorus cycled was presented based on the work reported in earlier studies. This helped to the understanding of the principles governing soil-P availability to crops, also necessary for the studies conducted in this work.

It appears from the information available in the literature that organomineral fertilisers made from nutrient enriched-coated-biosolids granules has not been used before. Their application does not appear to have been reported for experimental nor commercial purposes.

CHAPTER 3

PRODUCT SPECIFICATION

3 PRODUCT SPECIFICATION

3.1 Introduction

The technique proposed by United Utilities plc for the production of urea- and potash-coated biosolids granules was briefly described in **Chapter 1**, and a more detailed description of the coating process and the granulation of biosolids were provided in **Appendix A.1.1**. As highlighted earlier, the technique was used to produce two organomineral fertiliser (OMF) products: OMF_{15} and OMF_{10}. These have, approximately, the following NPK compositions: 15:4:4 and 10:4:4, respectively. This chapter explains the rationale behind the chosen OMF formulations and it discusses some of the advantages and disadvantages identified in the proposed products' compositions. The objectives of this chapter are summarised below:

- To develop the chemical specifications for a range of OMF products with suitable composition for application in winter wheat (*Triticum aestivum L.*) and rye grass (*Lolium perenne L.*),
- To determine the physical and chemical characteristics of the materials supplied by United Utilities plc for their use in the experimental work conducted in the laboratory, the glasshouse and the field studies between 2007 and 2010,
- To generate the required data to be able to investigate the aerodynamic properties of OMF studied in **Chapter 4**, and
- To provide practical recommendations.

3.2 Product formulation

The key aspects considered for the formulation of the products were: **a.** chemical analyses of a typical sample of biosolids; **b.** standard nitrogen application rates in winter wheat crops (e.g. RB209 – MAFF, 2000; Brentrup and Link, 2004; Rothamsted Research, 2006; Johnston and Poulton, 2009 – Broadbalk Experiment, Rothamsted Research); **c.** phosphate and potash application rates, mainly, in cereal crops; and **d.** general guidance given by United Utilities plc with regards to the maximum range of nitrogen concentration in the products and soil-P status in proximity of the wastewater treatment works. The proposed formulations aim at reducing the risk of soil-P build up when biosolids are applied routinely in grassland and arable cropping. Nitrogen concentrations in the OMF above 15% are technically possible. A potential drawback of increasing the mineral nitrogen content of the product above this level is that it could affect the amount of biosolids that are recycled through agriculture.

There is also a potential increase in the manufacturing cost of the products which can arise from sourcing larger amounts of urea-N needed for the coating of base biosolids granules. Chemical analyses conducted by United Utilities plc (**Table 3.1**) showed that base biosolids granules have relatively low concentration of nitrogen in relation to phosphorus; i.e. low N:P ratio, and that the content of potassium is almost negligible.

Table 3.1: Chemical analysis of base biosolids (source: United Utilities plc, 2006).

Determination	Base biosolids
Total nitrogen (%, w w^{-1})	2.90
[1]Total P (%, w w^{-1})	4.35
[2]Total K (%, w w^{-1})	0.15
N:P ratio	0.67

[1], [2]Expressed as: P_2O_5 and K_2O respectively.

As can be seen from the table above, the low content of nitrogen relative to phosphorus results in low N:P ratio (*c*.0.67). This can potentially lead to a build up of soil-P if biosolids are regularly applied to the crop to match its nitrogen requirements. Therefore, there is a need to increase the existing N:P ratio in the biosolids in order to reduce the risk of soil-P enrichment. This is important when recommendations for the application of biosolids are made on the basis of the crop nitrogen requirement. The build up of soil phosphorus above the target index for the soil and crop system can have undesirable consequences if subsequently phosphorus is lost to the environment. The formulation of OMF_{15} and OMF_{10} was made by coating base biosolids granules with nitrogen, in the form of urea (46%), and potassium, in the form of muriate of potash (60% K_2O), to produce a compound fertiliser of the form shown in **Figure 3.1**.

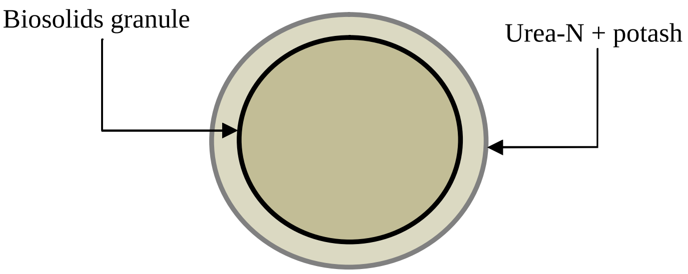


Figure 3.1: A schematic drawing of the OMF particle made of biosolids granules and coated with a layer of urea and potash.

It is important to highlight that the increase in the existing N:P ratio of base biosolids was done by increasing the content of mineral nitrogen since phosphorus cannot be easily removed from the biosolids. Hence, the content of phosphorus in the OMF is equivalent to that of the base biosolids. As highlighted earlier, typical nitrogen, phosphorus and potassium application rates to winter wheat were reviewed from the literature including the recommendations given in RB209 (MAFF, 2000), and the experimental data from the long term experiments on winter wheat at Rothamsted (Rothamsted Research, 2006) with particular regards to long term average crop yields and optimum nitrogen application rates (**Chapter 2**).

Following this information, it was assumed that the level of nitrogen in the soil was likely to be deficient, in most circumstances, to meet the nitrogen requirements of a wheat crop with an expected grain yield of 8 tonnes ha^{-1}. It was also considered that, a typical nitrogen application rate in winter wheat for approximately the same level of grain yield as indicated above was *c*.200 kg [N] ha^{-1}. With regards to the phosphorus and potassium contents of the products, it was necessary to take account of the nutrients' off-take by the crop in relation to the yield of the crop and also to the soil-P and -K indexes. As highlighted in (**Chapter 2**) a significant proportion of soils in Northern England (*c*.23%) were reported to have soil-P index 3 or greater (Skinner et al., 1992; Skinner and Todd, 1998). Although this information may not appear to be up-to-date, it is worth noting that United Utilities plc has informed that soil-P indexes in its land-bank for recycling remain relatively high. Hence, the availability of land for recycling of biosolids in the main operating area of the company is, to some extent, restricted by the level of soil phosphorus. In addition, in order for the company to meet annual disposal/recycling targets, biosolids need to be transported longer distances which suggested that soil-P indexes are generally high in the surroundings of the wastewater treatment works. It may be expected, however, that the overall decline in the application rates of primary nutrients observed in recent years, particularly in grasslands (Defra, 2009a), can result in soil P-indexes declining over time. This can provide some room to increase current levels of biosolids recycling if the trend was to continue. Based on the soil information available (Skinner et al., 1992; Skinner and Todd, 1998), the N:P ratio in the product needed to be adjusted to ensure sufficient supply of nitrogen and phosphorus was provided and that existing soil-P indexes were not significantly altered if continuous application of OMF was to be practiced. Soil-P and -K indexes 1 are low level in the soil. Therefore, a narrower N:P ratio in the product formulation is preferred in this situation to allow the indexes to be corrected overtime towards the corresponding target index. Soil index 2, for both P and K, corresponds to the target index; hence, the level of P-/K-fertilisation should ensure that the indexes are maintained.

The amount of phosphorus applied should be equivalent to that taken off with the crop so that the index remains relatively stable overtime. Therefore, a wider N:P ratio in the product formulation is more appropriate in this situation. Soil-P and -K indexes 3 are high level in the soil. Therefore, phosphorus and potash fertilisation may be reduced or even omitted without compromising crop yield significantly. The decision largely depends on the grain to fertiliser price ratio; however, fertiliser can still be applied to help maintaining the overall fertility status of the soil. **Table 3.2** shows the application rates of P_2O_5 and K_2O according to their levels in the soil as recommended in RB209 (MAFF, 2000). These application rates are required for winter wheat with an expected yield of 8 tonnes ha^{-1} (it assumes the straw from the previous crop in the rotation is ploughed in).

Table 3.2: Recommended application rates of P_2O_5 and K_2O (from RB209 – MAFF, 2000).

Soil-P or -K index	**---------------- Application rate (kg ha^{-1})**	**-----------------**
	P_2O_5	**K_2O**
Index 1	85	70
Index 2	60	45

Justification for the proposed formulations: Based on the composition of the biosolids given in **Table 3.1**, the amount of biosolids needed to meet the phosphorus requirements shown in **Table 3.2**, would be, approximately, 1955 and 1380 kg [biosolids] ha^{-1} for soil-P index 1 and 2 respectively. The application of these amounts of biosolids result in the nitrogen application rate being, respectively, 143 and 160 kg [N] ha^{-1} lower than the required rate by the crop. This means that, in percentage terms, the concentration of N in the biosolids should be increased from the current 2.9% to 10.2% and 14.5% respectively to be able to meet the required rate of nitrogen of 200 kg [N] ha^{-1}. With respect to potassium, the application of the same amount of biosolids would result in the potash application rate being, approximately, 67 and 43 kg [K_2O] ha^{-1} lower than that required for index 1 and 2 respectively. Similarly, the concentration of potash in the biosolids should be increased from the current 0.15% to 3.60% and 3.26% for index 1 and 2 respectively. From this simple analysis, the formulation of the products can be inferred as shown in **Table 3.3**. It is important to note that complex compound fertilisers have the advantage over blended compound fertilisers in that all particles will have the same chemical composition and physical properties whereas the characteristics of the various components of a blend can differ greatly. This can have implications during handling, transport and storage, and also during spreading as particles will be prone to segregation. For this reason, mixing biosolids granules with urea prills is restricted by the differences encountered in the characteristics of both materials.

Table 3.3: Proposed formulations for two organomineral fertilisers.

	------- Nutrient composition (%, w w^{-1}) -------			
Product	**N**	**P_2O_5**	**K_2O**	**Formulation**
OMF_{15}	14.50	4.35	3.60	15:4:4
OMF_{10}	10.20	4.35	3.26	10:4:4

The formulations shown in **Table 3.3** would be appropriate for winter wheat grown in soils with P- and K-indexes 1 or 2. However, this does not necessarily mean that the use of these products is restricted to these two situations only. For soils with P-index 0, if the aim is to correct the index, then a possible fertilisation strategy may be to combine the use of a straight phosphorus fertiliser with OMF_{10} so that the requirement of nitrogen is supplied with OMF_{10} and the balance of phosphorus is made up with the straight P-fertiliser source. Conversely, for soils with P-index 3 if the aim is not to run down the index, a possible fertilisation strategy may be to combine the use of urea and OMF_{15}. Similarly, the requirement for phosphorus will be met with OMF_{15} and the balance of nitrogen made up with a straight nitrogen source. For soil P-indexes above 3 the same principle may be applicable if the purpose is not to decrease the soil P-index. In situations where P- and K-indexes were different; e.g. low P and high K and vice versa, the use of straight fertiliser sources or more targeted blends would be more appropriate.

3.3 Characterisation of the products

With the exception of urea, all fertiliser materials were provided by United Utilities plc on an annual basis. This required that chemical analyses and characterisation of their physical properties were conducted annually for each fertiliser batch. Urea was purchased from a local supplier in 2007 and the same material was used for all trials in the subsequent years. The physical properties of urea were measured only once and the results are reported in **Section 3.4.4** with all other materials used in 2010. Chemical analyses of urea were not performed since the nitrogen content was indicated on the label in compliance with relevant legislation (UK Fertiliser Regulations 1991 Statutory Instrument No.: 2197, and EC Fertiliser Regulations No.: 2003/2003). The physical and chemical analyses conducted on the fertilisers and a brief description of the methods used is given in **Sections 3.3.1** and **3.3.2.** The results of the analyses for the fertiliser materials used between 2007 and 2010 are presented in **Sections 3.4.1** to **3.4.4** respectively. Particle density was measured for all materials in 2010 and the results of this measurement were used in the particle trajectory model (**Chapter 4**).

The statistical analyses are presented in **Appendices A.3.1**.

3.3.1 Chemical analyses

Chemical analyses were always determined on three sub-samples of fertilisers (n=3); the value quoted in the tables corresponds to the mean value of the 3 sub-samples analysed.

i. Total nitrogen in fertilisers

Total nitrogen was determined based on the Dumas technique (Dumas, 1831) and the specifications outlined in The Fertilisers (Sampling and Analysis) Regulations 1991 Statutory Instrument No.: 973.

ii. Total phosphorus, total potassium and heavy metals in fertiliser materials

The method is based on the specifications given in MAFF (1986), BS-7755-3.13 (1998) and The Fertilisers (Sampling and Analysis) Regulations 1991 Statutory Instrument No.: 973 and it uses Inductively Coupled Plasma Emission Spectroscopy. Determination of heavy metals in fertilisers included total Cd, total Cu, and total Zn. Heavy metals were only determined for OMF_{15}, OMF_{10} and biosolids granules supplied in 2007 to have an indication of the levels likely to find in these materials. These analyses were not repeated in the following years since the study of heavy metals was not the main part of this work. However, analyses were performed in Avenue Field in 2007 prior to the start of the experimental work, and subsequently in 2010 at the end of the field studies. These were conducted to monitor their levels and potential build up overtime. The results of the analyses of heavy metals in soil are reported in **Chapter 7**.

3.3.2 Physical characteristics

i. Particle size analysis

The specifications given in BS-EN-1235 (1995) for the sieving of solid fertilisers could not be strictly followed since the range of sieves available did not completely match that of the standard. For the analysis, a sample of fertiliser of *c*.500 g was passed through a series of sieves having the following apertures: 0.60, 1.18, 2.36, 3.35, 4.00, 5.00, 5.50, 7.10, 9.50, 12.50, 19.00, 25.00 and 37.00 mm. The sieves were placed on a shaker for approximately three minutes, and subsequently, the fertiliser retained was weighted and expressed as percentage of the total weight of the sample. Standard BS-EN-1235 (1995) also recommends the characterisation of fertiliser materials by providing the values of percentiles D_{16}, D_{50} and D_{84} which corresponds to the particle diameters below which 16%, 50% and 84% (by weight) of the fertiliser material can be collected after sieving (Persson, 1996).

The D_{50} value is equivalent to the median particle diameter (Miserque et al., 2008). The characterisation of a fertiliser material by the D_{16} and D_{84} percentiles is usually a more accurate measure than the D_{10} and D_{90} respectively (Lance, 1996). This is particularly important when the apertures of the sieves in the upper and lower parts of the curve are not sufficiently close and result in large intervals between two consecutive sieves. The calculation of the percentiles 10 and 90 by linear interpolation can lead to over/under estimation of the real values (Lance, 1996). In contrast, the calculation of the D_{16} and D_{84} percentiles can give more accurate estimates as it is more likely to fall within a more linear part of the curve for most materials. The D_{50} value is usually a reliable measurement as it always falls within the most linear part of the curve (Lance, 1996). In general, the physical and chemical properties of the materials differed greatly year on year. Therefore, the measurements of the physical properties reported in the following sections may not truly reflect those of the proposed formulations and these should be repeated in the future. The granulometric distribution curves are shown in **Appendix A.3.2**.

ii. Bulk density

Bulk density was determined following the specifications outlined in BS-EN-1236 (1995). The principle consists of pouring a fertiliser sample through a funnel and into a measuring cylinder and recording the weight and the volume occupied by the sample.

3.4 Results

3.4.1 Fertiliser materials used in 2007

The fertiliser materials supplied for the experiments in 2007 are shown in **Figure 3.2**.

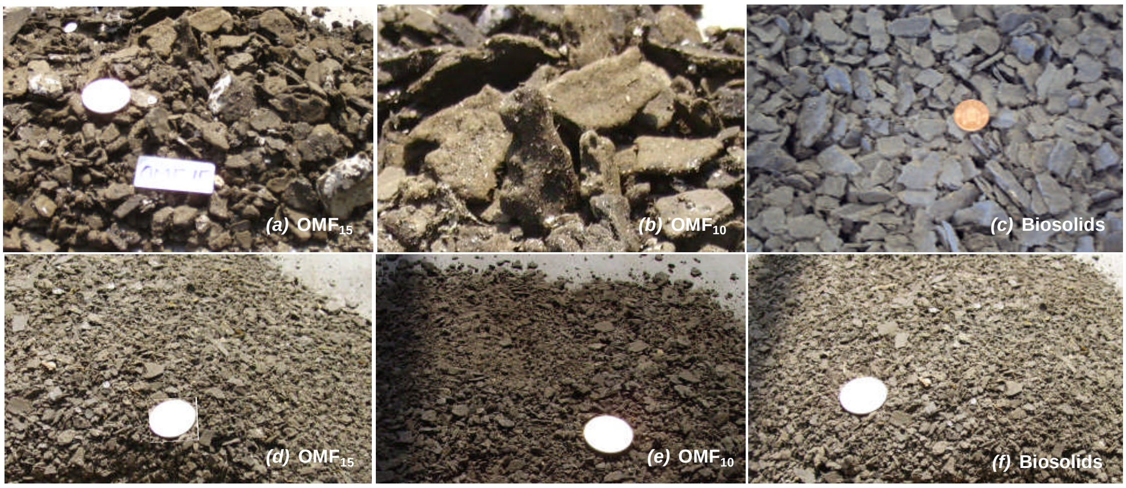


Figure 3.2: Fertiliser materials used in 2007 prior (*a, b,* and *c*) and after grinding (*d, e,* and *f*) for OMF_{15}, OMF_{10} and biosolids respectively [Note: *a, d, e, f,* 10 pence coin; *c,* 1 penny coin].

i. Chemical composition

The results of the chemical analyses for OMF_{15}, OMF_{10} and biosolids used in 2007 are shown in **Table 3.4**. The analysis of soluble phosphorus in water was only conducted for the fertiliser materials used in 2007. Due to the method used for the removal of phosphorus from the wastewater, the values of water soluble-P were, as expected, low. The method for determination of water soluble-P is described in MAFF (1986).

Table 3.4: Results of the chemical analyses conducted for the fertilisers supplied in 2007 (n=3).

2007	--------------- **Fertiliser material** ---------------		
Determination	**OMF_{15}**	**OMF_{10}**	**Biosolids**
Total N (%, w w^{-1})	9.83	8.13	3.89
[1]Total P (%, w w^{-1})	3.71	4.10	5.20
[2]Total K (%, w w^{-1})	2.05	2.33	0.14
Total Cd (mg kg^{-1})	0.98	0.98	1.20
Total Cu (mg kg^{-1})	268	264	329
Total Zn (mg kg^{-1})	422	422	493
P soluble in water (%, w w^{-1})	0.07	0.10	0.19
N:P ratio	2.65	1.98	0.75

[1], [2]Expressed as: P_2O_5 and K_2O respectively.

The chemical composition of the products differed from those of the specification (**Table 3.3**). The levels of heavy metals (Cd, Cu, and Zn) in all materials were found to be well below the recommended limit values given in EC Sewage Sludge Directive 86/278/EEC (CEC, 1986).

ii. Particle size analysis

The materials supplied in 2007 (**Figure 3.2**) were shape-flaked and presented relatively large particles; these required grinding prior to their soil application. The materials were ground to pass a 5.50 mm sieve and particle size analysis was conducted for all materials both prior and after grinding. Following the guidelines given in Standard BS-EN-1235 (1995), the materials were characterised by the values of percentiles D_{16}, D_{50} and D_{84}. The results of the particle size analysis are shown in **Table 3.5**. A statistical analysis of the particle size distribution was undertaken which included a t-test to compare the means and an F-test to compare the variation in the particle size distribution between the various fertiliser materials used. The t-test at 95% confidence interval showed significant differences with respect to the calculated mean value of particle size for comparisons between OMF_{15} and biosolids and also between OMF_{10} and biosolids (t-values of 5.26 and 4.63 respectively).

However, the differences in the particle size between OMF$_{15}$ and OMF$_{10}$ were nonsignificant (t =0.49). The F-test (α =0.05; 100 degrees of freedom) did not show significant differences for comparisons between any of the fertiliser materials (F-values were smaller than an F-critical value of 1.41; Rohlf and Sokal, 1995).

Table 3.5: Particle size analysis for the materials supplied in 2007, prior to grinding.

Sieve size	**Retained (%, w w^{-1})**		
(mm)	**OMF$_{15}$**	**OMF$_{10}$**	**Biosolids**
< 0.60	3.40	2.78	1.16
0.60 – 1.18	2.20	1.90	0.33
1.18 – 2.36	5.90	5.21	1.45
2.36 – 3.35	7.10	7.23	2.00
3.35 – 4.00	5.01	5.25	1.72
4.00 – 5.50	5.24	6.01	4.03
5.50 – 7.10	7.87	7.43	4.14
7.10 – 9.50	23.62	22.28	12.45
9.50 – 12.50	21.70	20.59	17.37
12.50 – 19.00	13.10	15.25	43.88
19.00 – 25.00	3.40	4.21	9.46
25.00 – 37.00	1.46	1.86	2.01
> 37.00	-	-	-
D_{16} (mm)	2.98	3.19	7.32
D_{50} (mm)	8.45	8.62	13.29
D_{84} (mm)	13.47	14.76	18.32
Mean (mm)	**8.88**	**9.29**	**13.16**
SD	**32.80**	**36.20**	**33.59**

The results of the particle size analysis conducted after the materials were ground are shown in **Table 3.6**.

Table 3.6: Particle size analysis for the materials supplied in 2007, after grinding.

Sieve size	**Retained (%, w w^{-1})**		
(mm)	**OMF$_{15}$**	**OMF$_{10}$**	**Biosolids**
< 0.60	7.28	5.39	10.32
0.60 – 1.18	16.72	9.59	13.09
1.18 – 2.36	25.80	29.05	22.96
2.36 – 3.35	38.80	39.82	33.95
3.35 – 4.00	5.80	7.04	5.79
4.00 – 5.50	6.10	9.11	13.89
> 5.50	-	-	-
D_{16} (mm)	0.91	1.22	0.85
D_{50} (mm)	2.37	2.50	2.46
D_{84} (mm)	3.24	3.36	3.76
Mean (mm)	**2.23**	**2.44**	**2.40**
SD	**1.29**	**1.28**	**1.79**

The results of the t-test at 95% confidence interval indicated that there were not significant differences with respect to the calculated mean particle size for any of the fertiliser materials after these were ground (t-values <1.96). The F-test (α=0.05; 100 degrees of freedom) did not show significant differences for comparisons between any of the fertiliser materials (F-values were smaller than an F-critical value of 1.41; Rohlf and Sokal, 1995). The proportion of fine particles (<0.60 mm) increased markedly after the fertilisers were ground which resulted in dustier materials. For OMF_{15} and OMF_{10}, the increase in the proportion of small particles was due to large clods of urea disintegrating into very fine particles during the grinding process. The moisture content (dry basis) of the materials was as follow: 19.1% (OMF_{15}), 16.7% (OMF_{10}), and 11.8% (biosolids). The smaller D_{16} value of OMF_{15} compared with OMF_{10} was due to the larger proportion of urea-clods present in the OMF_{15} breaking into very fine particles.

iii. Bulk density

The values of bulk density encountered for the fertiliser materials used in 2007 are shown in **Table 3.7**.

Table 3.7: Bulk density (ρ_b) and standard deviation of the mean (*SD* of mean) for the materials supplied in 2007 (n=3).

2007	----------------------- **Fertiliser type** -----------------------		
Before grinding	**OMF_{15}**	**OMF_{10}**	**Biosolids**
Mean ρ_b (kg m^{-3})	549.4	550.2	448.7
SD	1.39	0.82	1.02
2007	----------------------- **Fertiliser type** -----------------------		
After grinding	**OMF_{15}**	**OMF_{10}**	**Biosolids**
Mean ρ_b (kg m^{-3})	628.3	598.9	500.5
SD	0.02	3.04	1.33

The statistical analysis indicated that (before grinding), the bulk density of biosolids was significantly lower ($p<0.001$; $LSD_{[5\% \text{ level}]}$ =10.02) than OMF_{15} and OMF_{10} which was attributable to their overall larger particle size. In addition, urea (**Section 3.4.4**) was found to have a significantly higher value of bulk density compared with OMF_{15}, OMF_{10} and biosolids both before and after grinding the materials in 2007 (p-values <0.001; $LSD_{[5\% \text{ level}]}$ values of 10.02 and 10.71 respectively). In general, bulk density increased markedly after the materials were ground which was also due to the overall reduction in voidage and the increase in fine particles (<1.18 mm).

The higher bulk density value encountered for OMF_{15} compared with OMF_{10} was due to the overall smaller particle size range that resulted from the grinding OMF_{15} compared with OMF_{10}. The values of bulk density recorded after grinding were also significantly lower than that of urea ($p<0.001$; $LSD_{[5\% \text{ level}]} = 10.71$).

3.4.2 Fertiliser materials used in 2008

The fertiliser materials supplied for the experiments in 2008 are shown in **Figure 3.3**.

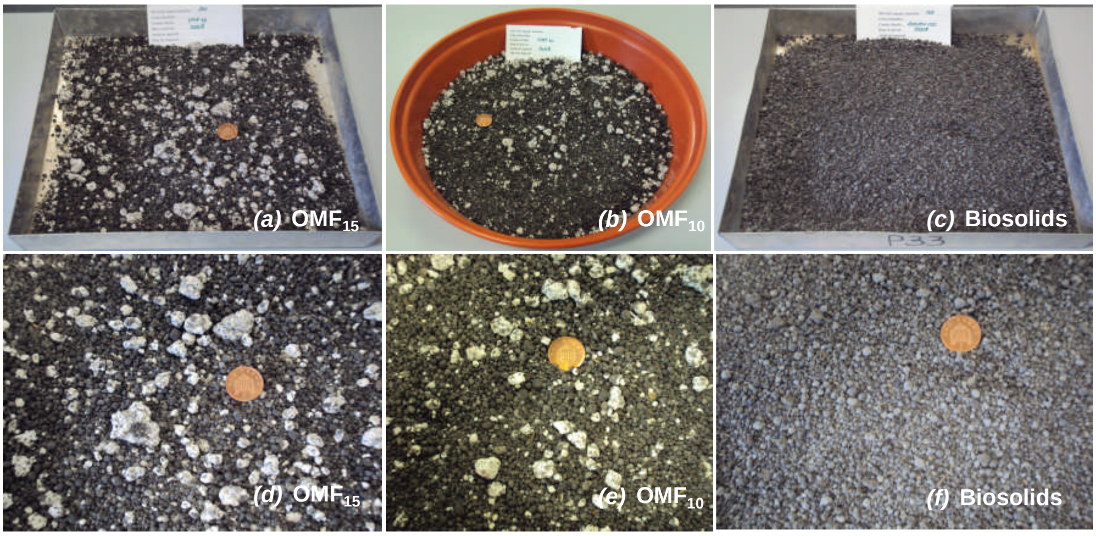


Figure 3.3: Fertiliser materials used in 2008 (top) and close-up of the samples (bottom) [Note: the coin shown in the pictures is 1 penny].

i. Chemical composition

The chemical composition of OMF_{15}, OMF_{10}, and biosolids granules used in 2008 is shown in **Table 3.8**. Although, the chemical composition of the products did not exactly match the specification, a significant improvement was made compared with 2007.

Table 3.8: Results of the chemical analyses conducted for the fertilisers supplied in 2008 (n=3).

2008	------------------------ Fertiliser material		---------------------
Determination	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**
Total N (%, w w^{-1})	16.05	10.52	4.53
[1]Total P (%, w w^{-1})	3.62	3.94	5.96
[2]Total K (%, w w^{-1})	3.85	3.57	0.26
N:P ratio	4.43	2.67	0.76

[1], [2]Expressed as: P_2O_5 and K_2O respectively.

ii. Particle size analysis

Significant improvements were made in 2008 with respect to 2007 with regards to the particle shape of the raw material which showed a more granular appearance. However, the final product still presented an important amount of urea-clods in both OMF_{15} and OMF_{10} samples (**Figure 3.3**). This was also reflected in the particle size analysis for the material retained above 5.50 mm (**Table 3.9**).

Table 3.9: Particle size analysis of OMF_{15}, OMF_{10} and biosolids granules (2008).

Sieve size (mm)	**Retained (%, w w^{-1})**		
	OMF_{15}	**OMF_{10}**	**Biosolids granules**
< 0.60	6.07	0.52	2.77
0.60 – 1.18	10.59	2.56	19.80
1.18 – 2.36	41.75	21.23	50.14
2.36 – 3.35	21.18	39.12	18.36
3.35 – 4.00	7.33	17.56	4.84
4.00 – 5.00	5.70	16.01	3.14
5.00 – 5.50	1.01	1.72	0.63
5.50 – 7.10	2.50	0.60	0.32
7.10 – 9.50	0.64	0.15	-
9.50 – 12.50	1.53	0.23	-
12.50 – 19.00	1.14	0.19	-
19.00 – 25.00	0.56	0.11	-
> 25.00	-	-	-
D_{16} (mm)	1.14	1.89	0.98
D_{50} (mm)	2.12	3.01	1.82
D_{84} (mm)	3.74	4.18	2.96
Mean (mm)	**2.72**	**3.10**	**1.97**
SD	**7.06**	**1.98**	**0.95**

The results of the t-test at 95% confidence interval indicated that there were not significant differences with respect to the calculated mean particle size for comparisons between OMF_{15} and OMF_{10} (t =1.28). In addition, the mean particle size of OMF_{15} and OMF_{10} were significantly higher compared with that of biosolids granules (t-values >1.96). The F-test (α=0.05; 100 degrees of freedom) showed significant differences for comparisons between all fertiliser materials (F-values were larger than an F-critical value of 1.41; Rohlf and Sokal, 1995).

iii. Bulk density

The values of bulk density encountered for the fertiliser materials used in 2008 are shown in **Table 3.10**.

Table 3.10: Bulk density (ρ_b) and standard deviation of the mean (*SD* of mean) for the materials supplied in 2008 (n=3).

2008	----------------------- **Fertiliser type** -----------------------		
Bulk density	**OMF$_{15}$**	**OMF$_{10}$**	**Biosolids granules**
Mean ρ_b (kg m^{-3})	605.9	625.1	640.0
SD	2.56	12.84	7.03

The statistical analysis showed that the mean value of bulk density for biosolids granules was significantly higher than that of OMF$_{15}$ ($p<0.001$; LSD$_{[5\%\ \text{level}]}$ =22.78). The differences encountered between OMF$_{10}$ and OMF$_{15}$ and also between OMF$_{10}$ and biosolids granules were nonsignificant (p-values >0.05). The relatively higher bulk density value of biosolids granules compared with OMF$_{15}$ and OMF$_{10}$ was due to the overall smaller particle size and hence the smaller proportion of voids encountered for biosolids granules. Urea (**Section 3.4.4**) showed a significantly higher ($p<0.001$) bulk density value compared with OMF$_{15}$, OMF$_{10}$ and biosolids granules for the same LSD value indicated above.

iv. Particle strength

Particle strength is likely to influence the distribution performance of fertiliser spreading equipment (Miller, 1996). It affects the particle motion in the distributor and it influences the ability of the fertiliser to withstand weight during storage and transport (Hofstee and Huisman, 1990). Fertiliser particles having insufficient strength are likely to break during motion in the distributor. When particles break, the particle size distribution of the fertiliser is affected this influences particle motion (Hofstee and Huisman, 1990). Small changes in particle diameter can have a significant effect on the landing distance of the particle when these are projected from a spinning disc of a fertiliser spreader.

Hofstee and Huisman (1990) identified three types of particle strength as follow:

- **Static particle strength:** it refers to the maximum load a particle can bear; i.e. the breaking force, divided by the cross-sectional area of the particle (Hofstee and Huisman, 1990). It can be determined by loading individual particles by means of compression and then recording the force needed to provoke the breaking of the particle (Hofstee and Huisman, 1990). Although there is no static load being applied during particle motion, static particle strength provides a reasonable estimate of the overall particle strength (Hofstee and Huisman, 1990);

- **Dynamic particle strength:** it refers to the capacity of a particle to resist a dynamic load such as the impact with the soil or during motion in the distributor. It can be determined by means of a shatter test and it is expressed as the percentage of particles degraded to fine (see Brübach, 1973; Brübach and Göhlich, 1973; Brinschwitz and Hagemann, 1980 for full details of the technique and experimental data);
- **Abrasion resistance:** it refers to the resistance of a particle to wear for example as a result of friction with other particles or the equipment (see Brübach, 1973; Brübach and Göhlich, 1973; Brinschwitz and Hagemann, 1980; Hignett, 1985 for details of the technique and experimental data). It is determined by rotating a fertiliser sample in a drum with metal balls and it is expressed as the percentage of particles degraded to fine. Abrasion resistance is important to reduce the formation of particles below 1 mm in diameter which are responsible for the increase in the coefficient of variation during spreading (Hofstee and Huisman, 1990).

This section is concerned with the determination of the force required to induce particle's fracture. Measurements were only conducted for the fertiliser materials supplied in 2008 and urea using a compression tester Instron 1122 (**Figure 3.4**).

Figure 3.4: A picture showing the Instron 1122 (Instron, 1975); (*a*) overview of equipment, (*b*) close-up, (*c*) chart-drive system, and (*d*) laptop computer to record the measurements.

The fertiliser particles were placed between the cross-head and the bottom of the frame. A load cell recorded the load applied to the particle and the information digitally stored in a laptop computer attached to the equipment until the fracture of the particle was observed. The equipment was calibrated prior to conducting the tests and the calibration curves are presented in **Appendix A.3.3**. The results obtained for urea, OMF_{15}, OMF_{10} and biosolids granules are shown in **Figures 3.5** and **3.6** respectively. The ranges of particles selected for the test were the following: 7.10-5.50, 5.50-4.00, 4.00-3.35, and 3.35-2.36 mm in diameter.

Moisture content in the materials was determined prior to the test for OMF_{15}, OMF_{10} and biosolids granules, and the mean values obtained were 17.34%, 14.95% and 10.77% respectively. It is not clear whether the mass change after oven-drying the fertiliser samples were due to changes in moisture content, ammonia volatilisation or both. However, as recorded by visual assessment, urea appeared to have been lost from the samples after drying. A statistical analysis was undertaken only for the test conducted on urea granules since it was not possible to identify a distinctive point corresponding to the breaking force of OMF and biosolids granules.

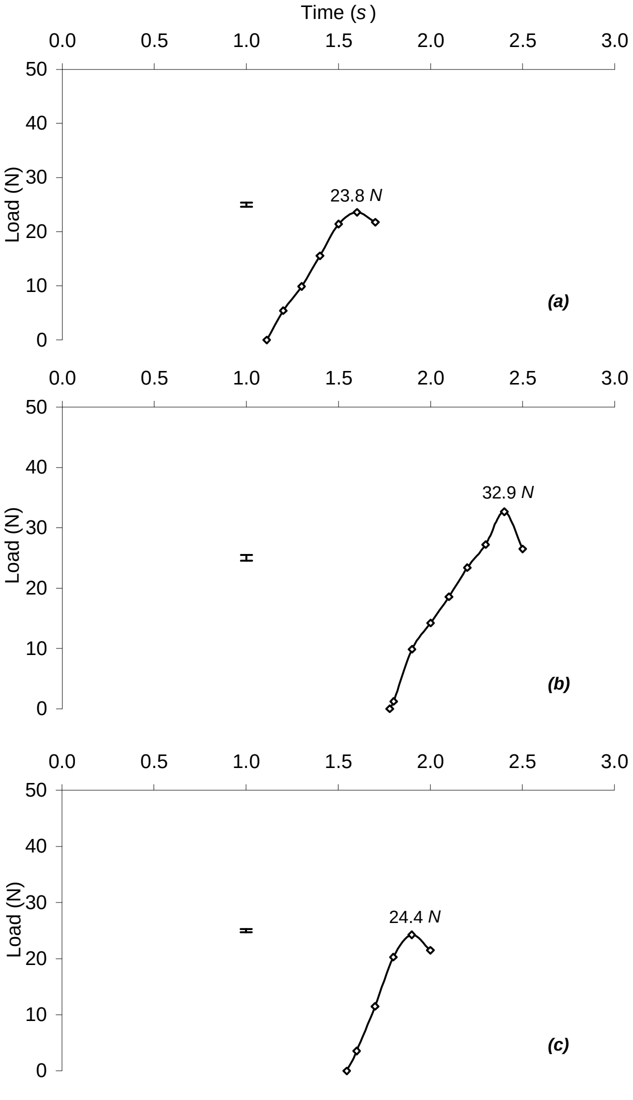


Figure 3.5: Compression tests for granular urea for a range of particle sizes; (*a*) 2.36-3.35 mm, (*b*) 3.35-4.00 mm, and (*c*) 4.00-5.50 mm. [The values indicated on the graph correspond to the mean breaking force and the vertical bars indicate the *SD* of the mean (*SD* values of 0.389, 0.485, and 0.290 for (*a*), (*b*) and (*c*) respectively; $LSD_{[5\% \text{ level}]}$ =1.26)].

The statistical analysis showed that there were significant differences in the breaking force of urea granules with respect to the size of the particle ($LSD_{[5\%\ level]}$ =1.26; p<0.001). Hignett (1985) suggested that the breaking force of granular urea must be greater than 15 *N* to prevent particle fracture during handling/spreading. In addition, Hofstee and Huisman (1990), based on the work of Kämpfe et al. (1982), Achorn and Broder (1984), and Hignett (1985), reported breaking forces for urea in the range of 10 to 30 *N*. **Figure 3.7** shows the result of the compression test for clods of urea in the range of 5.50 to 7.10 mm which were taken from a sample of OMF_{15}.

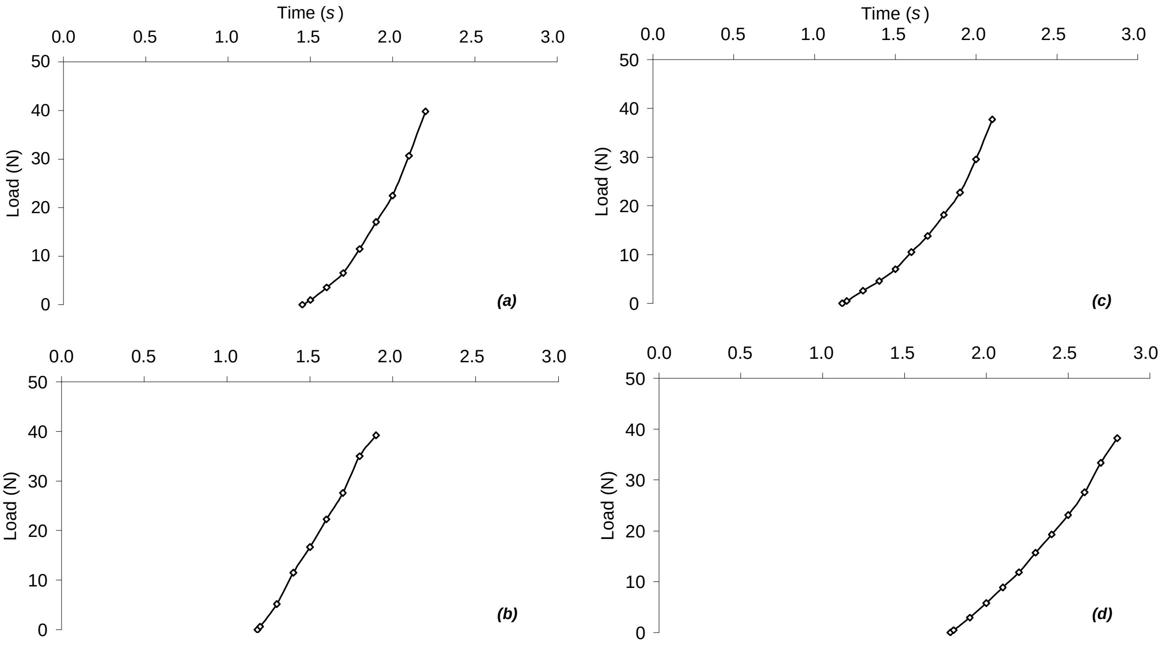


Figure 3.6: Compression test for OMF_{15} (2008) for a range of particle sizes; (*a*) 2.36-3.35 mm, (*b*) 3.35-4.00 mm, (*c*) 4.00-5.50 mm, and (*d*) 5.50-7.10 mm.

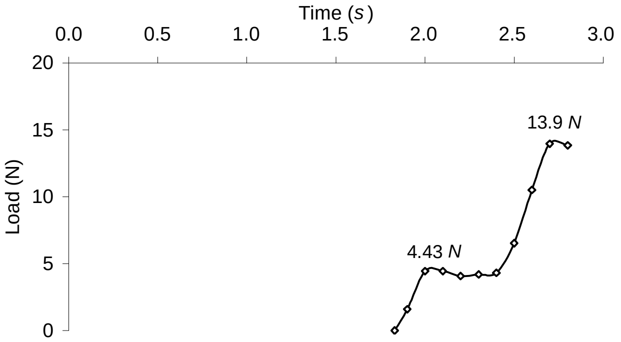


Figure 3.7: Compression test for clods of urea taken from a sample of OMF_{15} (2008) with particles in the range 5.50-7.10 mm.

The first peak in the curve recorded at 4.43 *N* corresponds to the point where the clod first breaks; this disintegrates into smaller particles which break later as the test progresses. Between 2.0 and 2.5 *s* approximately, there is a decline in the force recorded since the tester needs to travel further down until it reaches another clod. The curve shows that large clods can break relatively easy with a small force, and that the smaller particles formed can withstand more pressure; i.e. 4.43 *N* and 9.47 *N* respectively. It appears that the material losses strength compared with granular urea when re-aggregated in large clods during the production of OMF. The results of the compression tests for OMF_{10} and biosolids granules (2008) are shown in **Figures 3.8** and **3.9** respectively.

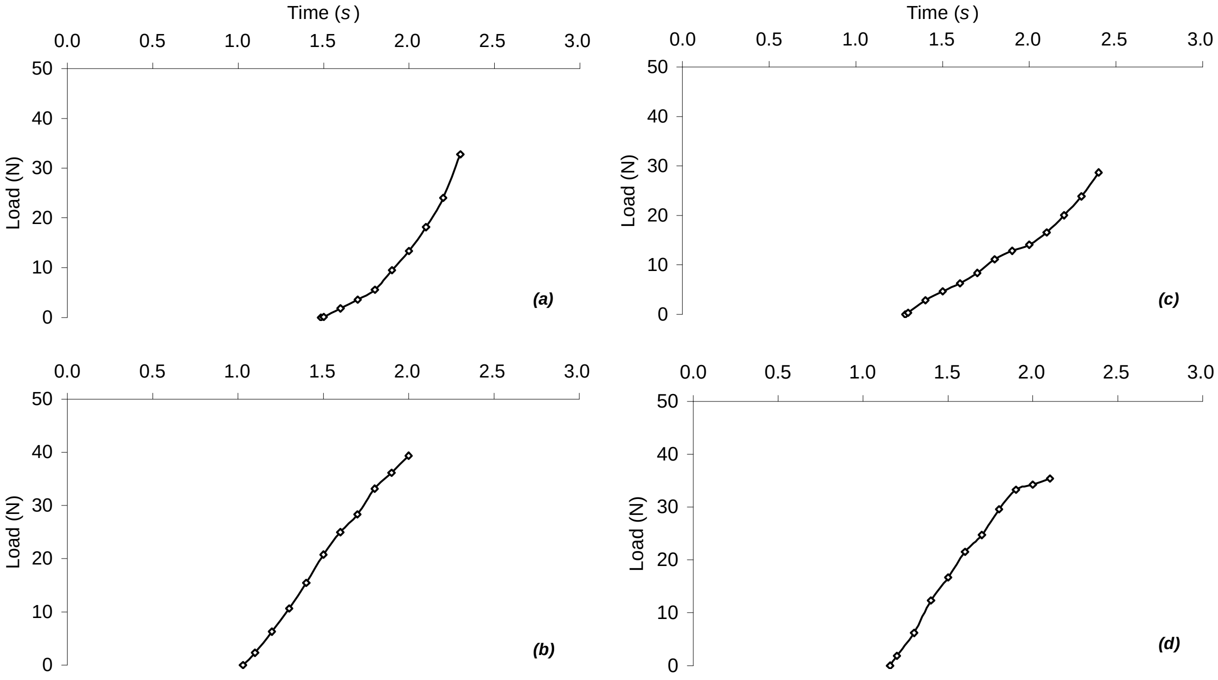


Figure 3.8: Compression test for OMF_{10} (2008) for a range of particle sizes; (*a*) 2.36-3.35 mm, (*b*) 3.35-4.00 mm, (*c*) 4.00-5.50 mm, and (*d*) 5.50-7.10 mm.

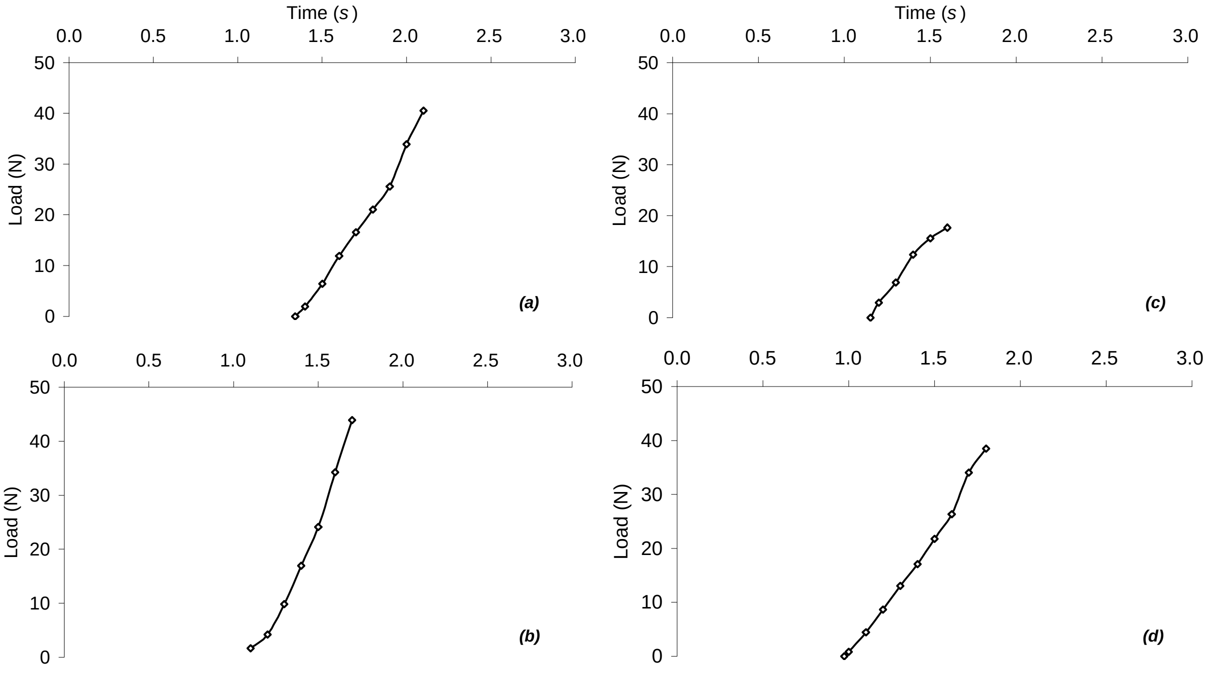


Figure 3.9: Compression test for biosolids granules (2008) for a range of particle sizes; (*a*) 2.36-3.35 mm, (*b*) 3.35-4.00 mm, (*c*) 4.00-5.50 mm, and (*d*) 5.50-7.10 mm.

The compression tests demonstrated that OMF_{15}, OMF_{10} and biosolids granules did not show a characteristic force that induced the fracture of the particles. Instead these showed multiple failure and they tended to deform when a relatively small force was applied behaving in a plastic way. Deformation started immediately after the tip of the instrument made contact with the particle and the test was allowed to progress until particles were fully compressed, as recorded by visual assessment during the tests. An important feature is that OMF and biosolids particles did not disintegrate into smaller particles as it was observed for urea. Particle's deformation can influence their aerodynamic properties as their shape is altered from its original pseudo-spherical condition (**Figure 3.10**). This plastic behaviour can be attributable to the moisture content and the organic nature of the materials. In order to minimise the effect of the moisture content on the strength of the particles, plastic packaging may be recommended, as suggested by Paré et al. (2009), and moisture content should be kept to a minimum (e.g. ≤10%).

Figure 3.10: A picture of OMF_{15}, OMF_{10} and biosolids granules in the range of 3.35 to 4.00 mm in diameter showing the aspect of the particles before and after the compression test was conducted.

3.4.3 Fertiliser materials used in 2009

The fertiliser materials supplied for the experiments in 2009 are shown in **Figure 3.11**.

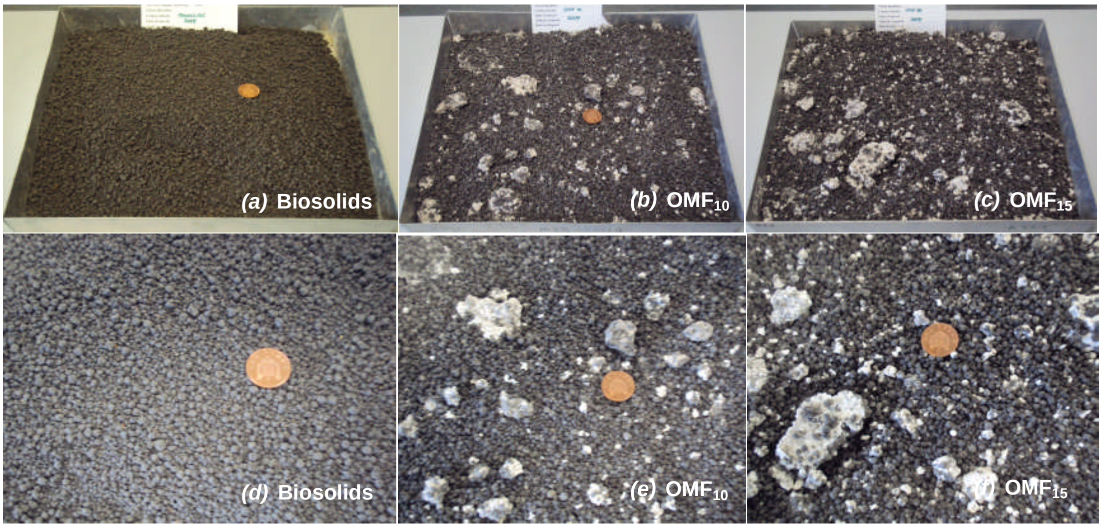


Figure 3.11: Fertiliser materials used in 2009 (top) and close-up of the samples (bottom) [Note: the coin shown in the pictures is 1 penny].

i. Chemical composition

The chemical composition of both OMF products and biosolids granules used in 2009 is shown in **Table 3.11**.

Table 3.11: Results of the chemical analyses conducted for the fertilisers supplied in 2009 (n=3).

2009	---------------------- **Fertiliser material** -----------------------		
Determination	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**
Total N (%, w w^{-1})	13.96	9.85	3.97
[1]Total P (%, w w^{-1})	4.07	5.09	6.57
[2]Total K (%, w w^{-1})	4.01	3.20	0.10
N:P ratio	3.43	1.94	0.60

[1], [2]Expressed as: P_2O_5 and K_2O respectively.

As can be read off the table, the composition OMF_{15} and OMF_{10} was close to the specification. It is important to highlight the relatively lower N:P ratio encountered for the biosolids granules in 2009 compared to the values recorded for 2007 and 2008 (N:P ratios 0.67 and 0.76 respectively).

ii. Particle size analysis

As highlighted for 2008, the materials used in 2009 also presented large amounts of urea-clods formed during the production of OMF. The range of particle sizes (**Table 3.12**) was larger than that of the previous year with particles being retained in the range of 25 to 37 mm in diameter.

Table 3.12: Particle size analysis of OMF_{15}, OMF_{10} and biosolids granules (2009).

Sieve size	--------------------------- **Retained (%, w w^{-1})**	---------------------------	
(mm)	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**
< 0.60	2.75	1.04	0.42
0.60 – 1.18	1.67	0.93	7.26
1.18 – 2.36	10.32	18.94	50.33
2.36 – 3.35	53.47	52.51	29.13
3.35 – 4.00	13.79	9.85	9.71
4.00 – 5.00	3.14	2.38	2.72
5.00 – 5.50	1.40	0.26	0.43
5.50 – 7.10	1.65	0.51	-
7.10 – 9.50	1.48	0.46	-
9.50 – 12.50	1.62	1.17	-
12.50 – 19.00	2.94	4.55	-
19.00 – 25.00	3.76	2.16	-
25.00 – 37.00	2.01	5.24	-
>37.00	-	-	-
D_{16} (mm)	2.38	2.05	1.37
D_{50} (mm)	3.02	2.91	2.17
D_{84} (mm)	4.63	4.30	3.24
Mean (mm)	**4.77**	**5.34**	**2.29**
SD	**33.59**	**52.77**	**0.75**

The results of the t-test (95% confidence interval) showed that there were not significant differences in the mean particle size between OMF_{15} and OMF_{10} (t =0.61). However, the mean particle size of biosolids granules was significantly smaller than that of OMF_{15} and OMF_{10} (t-values of 4.23 and 4.17 respectively).

The F-test (α=0.05; 100 degrees of freedom) showed significant differences for an F-critical value of 1.41 (from Rohlf and Sokal, 1995) for comparisons between OMF_{15} and OMF_{10} with biosolids granules respectively (F-values of 44.64 and 70.14 respectively). The differences in the particle size distribution between OMF_{15} and OMF_{10} were nonsignificant (F =0.63).

iii. Bulk density

The values of bulk density encountered for the fertiliser materials used in 2009 are shown in **Table 3.13**.

Table 3.13: Bulk density (ρ_b) and standard deviation of the mean (*SD* of mean) for the materials supplied in 2009 (n=3).

2009	------------------------ **Fertiliser type**	----------------------------	
Bulk density	**OMF$_{15}$**	**OMF$_{10}$**	**Biosolids granules**
Mean ρ_b (kg m^{-3})	551.6	573.5	613.1
SD	13.19	1.35	3.48

The statistical analysis showed that the mean value of bulk density for biosolids granules was significantly higher than the corresponding to OMF$_{15}$ and OMF$_{10}$ respectively (p<0.001; LSD$_{[5\%\ \text{level}]}$ =21.34). Although small, the difference between OMF$_{15}$ and OMF$_{10}$ was statistically significant for the same LSD value indicated above. As shown for 2008, a higher bulk density value of biosolids granules compared with OMF$_{15}$ and OMF$_{10}$ can be explained by the overall smaller particle size (**Table 3.12**) and hence the smaller proportion of voids encountered for biosolids granules. The bulk density of urea (**Section 3.4.4**) was also significantly higher compared with OMF$_{15}$, OMF$_{10}$ and biosolids granules respectively (p<0.001; LSD$_{[5\%\ \text{level}]}$ =21.34).

3.4.4 Fertiliser materials used in 2010

In addition to urea which was used in the previous years, **Figure 3.12** shows the materials supplied for their use in the experiments in 2010.

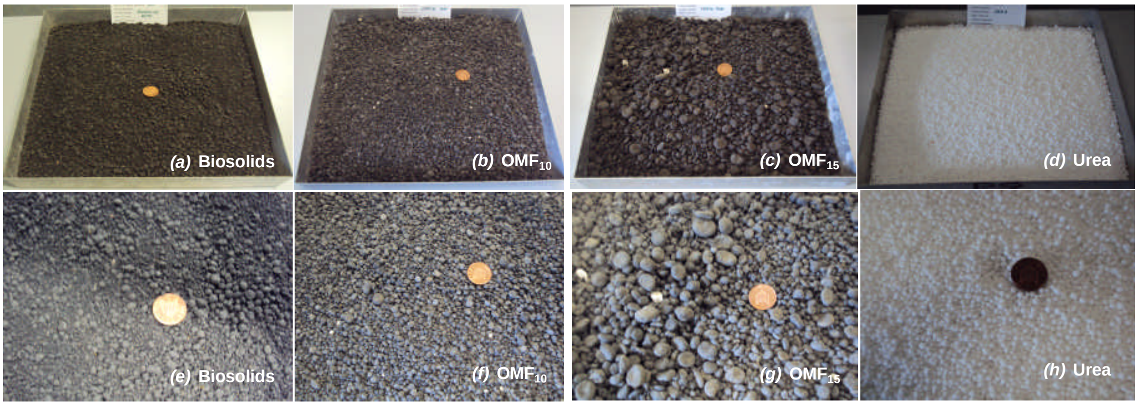


Figure 3.12: Fertiliser materials used in 2010 and urea used between 2007 and 2010 [Note: the coin shown in the pictures is 1 penny].

Later in 2010, improvements were made with regards to the optimisation of the coating process. A device was manufactured to spray melted urea on the base biosolids granules and to produce a thin layer of urea around the particle. The aspect of the final product is shown in **Figure 3.13** for OMF_{15}. Although this product was not available at the time the materials were required for their application in the field experiments in 2010, it shows that improvements are being made to optimise the coating process.

Figure 3.13: A sample of OMF_{15} produced after coating biosolids granules sprayed with melted urea. Particle sizes in the range of 2.80 to 5.60 mm in diameter. [Picture facilitated by United Utilities plc].

i. Chemical composition

The results of the chemical analyses of OMF_{15}, OMF_{10}, and biosolids granules used 2010 are shown in **Table 3.14**. The chemical composition of urea is reported in accordance with the analysis provided in the label and it corresponds to the same material used in previous years.

Table 3.14: Chemical composition of urea (2007-2010) and the fertiliser materials supplied in 2010 (n=3 except urea).

2010	---------------------------- **Fertiliser material** -------------------------			
Determination	**Urea**	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**
Total N (%, w w^{-1})	46	11.39	7.15	5.48
[1]Total P (%, w w^{-1})	-	3.55	4.17	4.32
[2]Total K (%, w w^{-1})	-	2.83	2.39	0.20
N:P ratio	-	3.21	1.72	1.27

[1], [2]Expressed as: P_2O_5 and K_2O respectively.

An important feature was the lower P_2O_5 content of the biosolids granules supplied in 2010 compared to the values reported for 2008 and 2009.

This value was of similar order of magnitude to that provided by United Utilities plc (**Table 3.1**) in 2006 upon which the product specification was based. The OMF produced for 2010 were not made to specification with approximately 25% to 30% lower nitrogen content than required.

ii. Particle size analysis

As can be seen from the pictures (**Figure 3.12**) the physical quality of the materials was improved in 2009 compared with previous years as samples showed very few clods of urea. The particle size analysis for the fertiliser materials used in 2010, including urea, is shown in **Table 3.15**.

Table 3.15: Particle size analysis of urea (2007-2010), and OMF_{15}, OMF_{10} and biosolids granules (2010).

Sieve size	----------------------------- Retained (%, w w^{-1}) -----------------------------			
(mm)	Urea	OMF_{15}	OMF_{10}	Biosolids granules
< 0.60	0.01	0.38	0.36	0.77
0.60 – 1.18	0.01	0.13	0.13	10.71
1.18 – 2.36	5.66	1.64	13.32	44.19
2.36 – 3.35	65.23	9.47	40.45	18.61
3.35 – 4.00	22.59	16.14	22.23	14.15
4.00 – 5.00	6.39	28.04	18.61	10.05
5.00 – 5.50	0.11	16.86	2.11	1.25
5.50 – 7.10	-	14.11	1.23	0.27
7.10 – 9.50	-	6.05	0.82	-
9.50 – 12.50	-	5.84	0.74	-
12.50 – 19.00	-	1.34	-	-
>19.00	-	-	-	-
Mean (mm)	**3.09**	**5.29**	**3.38**	**2.47**
SD	**0.35**	**5.60**	**1.57**	**1.32**

The values of percentiles D_{16}, D_{50} and D_{84} for the fertilisers used in 2010 are reported in **Table 3.16**. The results of the t-test (95% confidence interval) showed that there were significant differences with respect to the calculated mean value of particle size since all comparisons resulted in t-values greater than 1.96. The F-test (α=0.05; 100 degrees of freedom) showed significant differences for comparisons between OMF_{15} and OMF_{10} and also between OMF_{15} and biosolids granules (F-values of 3.58 and 4.34 respectively compared to an F-critical value of 1.41; Rohlf and Sokal, 1995). The materials reported in this section were also characterised by the GSI (%) which is known as the granulometric spread index **[Equation 3.1]**, as described in Lance (1996) and Miserque et al. (2008).

The GSI is known as the mean size range variation coefficient (Lance, 1996) and it can be estimated as follows (from Lance, 1996; Miserque et al., 2008):

$$GSI = \frac{[D_{84} - D_{16}]}{2 \times D_{50}} \times 100 \qquad \textbf{[3.1]}$$

This index is frequently used to characterise bulk blend fertiliser materials; it provides an indication of the likelihood of segregation. Segregation is the separation/re-arrangement of particles as a result of differences in their physical characteristics (Lance, 1996; Bridle et al., 2004). In order for segregation to occur, there must be movement between the particles (Lance, 1996). This phenomenon is not limited to blends as it can also take place with complex/compound fertilisers having a wide range of particle sizes (Lance, 1996). The effect of vibration which can take place during transport, handling and spreading, enhances segregation by making smaller particles to percolate through the voids left by larger particles (Stairmand, 1962). There could also be a combined effect of the particle size and particle density on segregation when particle density tends to decrease with the increase in particle diameter. As a result, the movement of smaller and denser particles through the voids towards the bottom of the hopper is enhanced. This relationship between particle size and particle density is shown later in **Figure 3.15** for urea, OMF_{15}, OMF_{10} and biosolids granules.

Miserque and Pirard (2004) suggested that in order to minimise the occurrence of granulometric segregation during loading, the GSI should be lower than 15. Values of GSI above 25 were reported to produce severe segregation. This mechanism of particle segregation can also increase the risk of uneven distribution of nutrients in the field, particularly for blends (Bridle et al., 2004), but also for low quality compound fertilisers whose particles do not have similar chemical composition. For non-blended fertilisers (both straight and compounds), if segregation took place before loading the fertiliser on the spreader, the spreading width can be severely affected (Bradley and Farnish, 2005). This is due to fine and large particles coming through in turn when loading the spreading equipment and subsequently being delivered at different times during spreading resulting in under/over-dosed areas respectively (Bradley and Farnish, 2005). The effect of segregation can be mitigated by selecting fertiliser materials having a close size grading (Bradley and Farnish, 2005).The work conducted by Miserque and Pirard (2004) also indicated that, in the case of blends, the difference between D_{16} and D_{84} (in absolute terms) should not exceed 0.5 mm as above this value segregation becomes significant.

Stairmand (1962) stated that the most important factor affecting segregation is particle size and that particle density and shape have only a limited effect. Hoffmeister et al. (1964) working with blended fertilisers demonstrated that segregation during handling and spreading was mainly due to differences in the particle size of the components of the blend whereas particle density was shown to have a small effect on segregation. The granulometric spread indexes as calculated in form shown in **Equation [3.1]** for the four fertiliser materials used in 2010 are presented in **Table 3.16**.

Table 3.16: Granulometric spread indexes and $D_{16\text{-}50\text{-}84}$ percentiles and probability of segregation for urea and the fertiliser materials supplied in 2010.

	---------------------- Fertiliser type	------------------------			
Parameter	**Urea**	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**	**Unit**
D_{16}	2.52	3.58	2.41	1.30	(mm)
D_{50}	3.03	4.79	3.25	2.21	(mm)
D_{84}	3.73	7.10	4.40	3.80	(mm)
GSI	19.9	36.74	30.61	56.56	(%)
[*]Probability of segregation	High	Very high	Very high	Very high	-

[*]This is only indicative and it is based on the calculated GSI values and those reported in Miserque and Pirard (2004).

Given the values of GSI shown in **Table 3.16**, it is possible to state that segregation is likely to occur and therefore the uniformity of distribution can be significantly affected.

iii. Particle density

The importance of particle density is that it influences particle's terminal velocity; hence the trajectory of a particle during spreading can also be affected by changes in particle density (Brübach, 1973). Particle density was estimated by measuring the diameter, and calculating the volume, of individual fertiliser particles from a sample of fertiliser containing approximately 100 particles and by recording the mass of the particles individually. Particle diameter was measured using a digital vernier calliper and the rationale for measuring it is shown in **Figure 3.14**. With the exception of urea, which was approximately spherical and its particle diameter was measured only in one direction (*C*-*D*), a mean diameter was obtained for the other three fertiliser materials. This was achieved by measuring the elongation of individual particles in the sample in two (*A*-*B*; *C*-*D*) for biosolids and OMF_{10} or three directions (*A*-*B*; *C*-*D*; *E*-*F*) for OMF_{15} to account for the unevenness in the fertiliser particle's shape as shown in **Figure 3.14**.

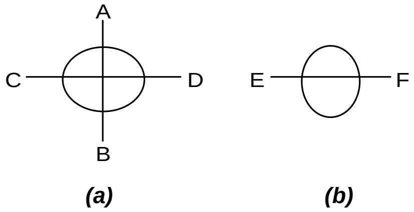


Figure 3.14: A fertiliser particle showing the rationale for measuring the particle diameter; (*a*): plan view, and (*b*): cross-sectional view.

The mean diameter was subsequently used to calculate the volume and it was assumed that the particle was spherical. The particle density was obtained by dividing the particle mass by the calculated volume for each particle and then by obtaining the mean value for the sample. An alternative method for measuring particle density includes that used by Aphale et al. (2003) and Miserque et al. (2008) whereby a small fertiliser sample of known mass is poured into a graduated glass cylinder filled with water and the displacement of water is then determined. Despite the efforts, this method could not be applied satisfactorily for OMF and biosolids granules as very fine particles (≤0.6 mm) remained suspended on the surface. Mean values of particle density obtained for the four fertiliser materials used in 2010 are shown in **Table 3.17**.

Table 3.17: Mean particle density (ρ_p) and standard deviation of the mean (*SD* of mean) for the four fertiliser materials used in 2010 (n=3).

2010	------------------------------ **Fertiliser type** ------------------------------			
Particle density	**Urea**	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**
Mean ρ_p (kg m^{-3})	1432	1357.0	1296.8	1332.8
SD	254.70	177.51	262.75	314.96

The statistical analysis showed that, overall, mean values of particle density were significantly different (p=0.002; $LSD_{[5\% \ level]}$ =73.2). However, these differences were mainly due to the effect of urea whose mean particle density was significantly higher than the rest of the fertiliser materials for the LSD value given above. Mean particle diameters measured in the sample were, as expected, significantly different (p<0.001) for all fertiliser materials except for comparisons between urea and biosolids granules (mean values of 3.71 and 4.04 mm respectively; $LSD_{[5\% \ level]}$ = 0.334). The value of particle density obtained for urea falls within the range (1260-1460 kg m^{-3}) reported in the literature for granular urea (Hoffmeister et al., 1964; Aphale et al., 2003; Parkin et al., 2005).

Similarly, the values encountered for the two OMF and biosolids granules were found to be within the range of values reported by Allaire and Parent (2004) and Paré et al. (2009) for organic-based fertilisers (899-1579 kg m^{-3} and 1007-2100 kg m^{-3}, respectively). These values, however, were obtained for bulk-blended organic-based fertilisers and do not strictly correspond to the type of materials used in this research. Allaire and Parent (2004) highlighted that particle density was found to decrease with increasing organic matter content in the fertiliser. With the exception of biosolids granules, the values shown for OMF_{15} and OMF_{10} in **Table 3.17** appear to be consistent with this observation. The measured values of particle density were regressed against those of particle diameter as shown in **Figure 3.15**.

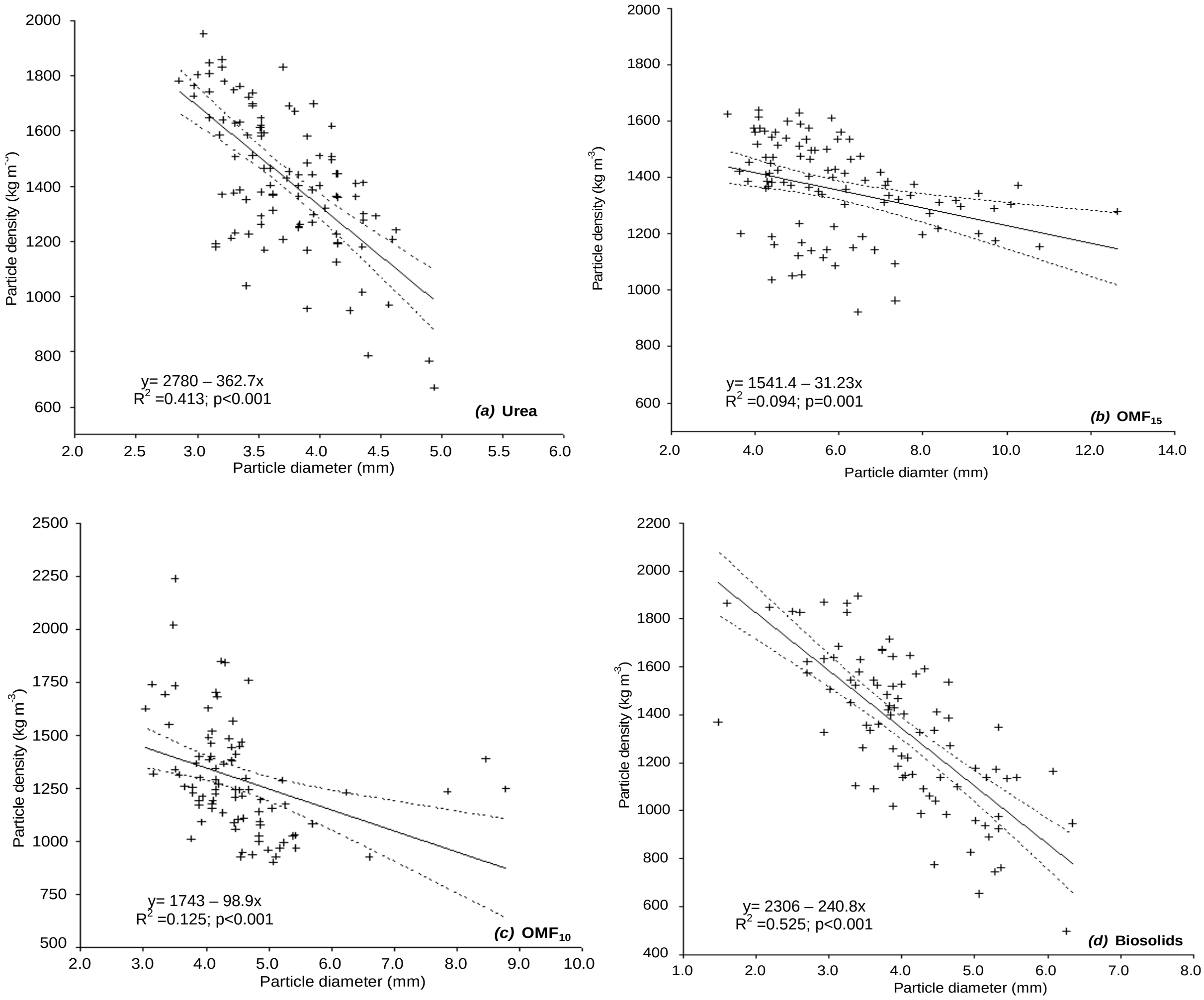


Figure 3.15: Relationship between particle density and particle diameter for the fertiliser materials used in 2010; (*a*) urea, (*b*) OMF_{15}, (*c*) OMF_{10} and (*d*) biosolids granules. The two curves on both sides of the fitted line represent its 95% confidence interval (n=100).

The relationships shown in **Figure 3.15** were found to be significant for all of the fertiliser materials used in 2010 (p-values <0.001 for urea, OMF_{10} and biosolids, and p=0.001 for OMF_{15} respectively). To some extent, these relationships could be influenced by the technique used for determining the particle's diameter and the lack of spherical shape of the particles in the samples (a greater error could have been introduced with increased particle diameter). The particle size analysis for biosolids granules showed a larger proportion of small particles (<2.36 mm) than OMF_{10} which resulted, overall, in higher particle density (**Table 3.15**).

iv. Bulk density

The values of bulk density obtained for the fertilisers supplied in 2010 and urea are shown in **Table 3.18**.

Table 3.18: Mean bulk density (ρ_b) and standard deviation of the mean (*SD*) for the four fertiliser materials used in 2010 (n=3).

2010	------------------------------ **Fertiliser type** ------------------------------			
Bulk density	**Urea**	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**
Mean ρ_b (kg m^{-3})	748.1	705.4	742.1	609.5
SD	6.96	1.07	0.66	13.71

The statistical analysis indicated that, overall, there were significant differences (p<0.001) in bulk density between the fertilisers. However, the mean value of bulk density obtained for urea and OMF_{10} were not statistically different for an $LSD_{[5\% \text{ level}]}$ value of 21.42. The relatively lower bulk density value of OMF_{15} compared with OMF_{10} is explained by its overall larger particle size (**Table 3.15**) and hence the larger proportion of voids present in the OMF_{15} sample.

v. Particle shape

Investigations into the particle shape and its influence on the aerodynamic behaviour of fertiliser particles include the work of Aphale et al. (2003), Miserque and Pirard (2004), and Walker et al. (1997). The later work employed a digital imaging system and calculated a particle's shape factor which was related to the lack of fit area of a particle's image to the best fit circle. Subsequently, a relationship was established between drag coefficients (C_D, turbulent flow) as a function of the calculated shape factors. The values of C_D thereby estimated were applied to trajectory modelling. The trajectory particle model studied in Chapter 4 regarded the fertiliser particles to be spherical. Mennel and Reece (1963) highlighted that this is a reasonable assumption for most particle shapes likely to be distributed with a centrifugal fertiliser spreader.

3.5 Conclusions

The main conclusions coming from **Chapter 3** are summarised below:

- Two organomineral fertilisers products (OMF) were suggested; these were: OMF_{10} (10:4:4) and OMF_{15} (15:4:4). These two formulations were proposed for their use on both grassland and arable cropping.
- Due to the narrower N:P ratio of OMF_{10} compared with OMF_{15}; it appears that this formulation would be more appropriate for situations with lower soil-P index. However, the application of the products should not be restricted to a single situation and they may be used in combination with alternative fertiliser sources to match specific crop-soil requirements.
- The chemical composition of the materials was not consistent between the various fertiliser batches. The fertilisers were not made to specification in some circumstances which provided a source of variation to the experimental results reported in the following chapters.
- The nitrogen concentration in the products was found to be in the range of 9.83% and 16.05% for OMF_{15} and 7.15% to 10.52% for OMF_{10}.
- In general, the physical properties varied widely between the various fertiliser batches, particularly, with regards to particle size and size distribution. Particles were found to be in the range of <0.60 mm (up 3% and 6% in OMF_{10} and OMF_{15} respectively) to 37 mm (up to 5.24% and 2% in OMF_{10} and OMF_{15} respectively) in diameter. The following values were encountered on average:
    - OMF_{10}: D_{50} =4.45 mm (range 2.91 to 8.62 mm); D_{16} =2.39 mm (range 1.89 to 3.19 mm); D_{84} =6.91 mm (4.18 to 14.76 mm);
    - OMF_{15}: D_{50} =4.60 mm (range 2.12 to 8.45 mm); D_{16} =2.52 mm (range 1.14 to 3.58 mm); D_{84} =7.16 mm (3.14 to 13.47 mm).
- As a result of the relatively wide range of particle sizes encountered, and based on the calculated GSI index, particle segregation is likely to occur during handling and spreading which can affect fertilisers' distribution uniformity. This could be enhanced as a result of the ρ_p to particle diameter relationships encountered.
- The particle and bulk densities values encountered in OMF_{10} and OMF_{15} were, on average, lower than that of urea which was expected given the nature of the products.

On average (2007-2010) bulk density for OMF_{10} was 622.7 kg m^{-3} (range of 550.2 to 742.1 kg m^{-3}) and 603.1 (range of 549.4 to 705.4 kg m^{-3}). For biosolids and urea these were on average 5.77.8 and 748.1 kg m^{-3}. Particle density was found to be (on average, based on 2010's samples) 1296.8 kg m^{-3} (range of 904.2 to 2239.9 kg m^{-3}) and 1357.0 kg m^{-3} (range of 713.1 to 1638.2 kg m^{-3}) for OMF_{10} and OMF_{15} respectively.

- The compression tests conducted showed that OMF particles tended to deform when a relatively small force was applied. Deformation started well below the lower limit suggested in earlier studies for urea to prevent particle fracture during handling and spreading (15 *N*). Particles did not show a characteristic breaking force that induced fracture of the particles; instead, these showed multiple failures. This behaviour was attributed to the relatively high moisture content of the material (≥10% w w^{-1}) and its organic nature.
- From the above, it appears that moisture content needs to be maintained to a minimum (e.g. ≤10% approximately) as particle deformation can affect their aerodynamic properties. Plastic packaging may be required during storage to protect their physical characteristics but this requirement needs investigating.
- Improvements in the physical and chemical characteristics of the products are required.
- The physical properties reported in this chapter will be used in **Chapter 4** for the particle trajectory model.

CHAPTER 4

FERTILISER PARTICLE AERODYNAMICS

4 Fertiliser particle aerodynamics

4.1 Introduction

Following the study of the physical properties of the four fertiliser materials used in this research; this chapter will investigate the fertiliser particle aerodynamics using the information reported in **Chapter 3**. In addition, a spreading test was conducted in the field using a pneumatic fertiliser applicator. The test was conducted with OMF_{15} prior to the application of fertiliser to the demonstration plots at United Utilities plc experimental site at Field Farms in Broxton (Cheshire). The aim of this study was to investigate the spreading performance of organomineral fertilisers and to aid in the calibration of the equipment before the fertilisers were applied to the plots. The objectives of this chapter are summarised below:

- To investigate the fertiliser particle dynamics off-the-disc to be able to predict the landing distance of individual fertiliser particles,
- From the above, to provide practical recommendations, and
- To report the results of the spreading test conducted in the field using a pneumatic fertiliser applicator.

It is well documented that uneven spreading of fertilisers can result in undesirable consequences on the environment, the performance of the crop and also economics (Dilz and van Brakel, 1985; Richards, 1985; Miller, 1996; Miller and Parkin, 2005; Miller et al., 2009). Richards (1985) highlighted that inaccurate fertiliser spreading can result from improper rate of application and also uneven spreading. The later author emphasised that the application of the correct rate of fertiliser depends on both the accuracy in determining the optimum rate and its precise application. Miller (1996) highlighted that there are a number of components of the application system which can affect the performance targets in relation to the delivery rate and uniformity of distribution. These, as listed by Miller (1996), include the following:

- Machinery design (Olieslagers et al., 1996),
- Machinery settings, calibration and maintenance (Bull and Crowe, 1985),
- Physical and chemical properties of the fertiliser material (Hofstee, 1993), and
- Weather conditions; e.g. wind speed – influencing particle’s trajectory (its effect is relatively low when it stays below 10 m s^{-1}), and relative air humidity – influencing the behaviour of the material (Svensson, 1994).

Fertiliser particle motion has been widely investigated. Studies into the particle dynamics on a spinning disc and the factors affecting it include the work conducted by Inns and Reece (1962) and Patterson and Reece (1962) for off- and near-centre feed conditions respectively, and later by Hofstee (1995), Aphale et al. (2003) and Grift et al. (2006). Following the work of Aphale et al. (2003) and assuming solid spherical particles, the analysis of the particle dynamics on a spinning disc can be made for two different conditions of particle movement on the disc; namely, pure sliding and pure rolling conditions. These two conditions have different solutions to predict the time at which the particle leaves the spinning disc and full explanation of the mathematical procedure for its calculation can be found in Aphale et al. (2003).

The terminal velocity of the particle at the instant at which it leaves the spinning disc includes both radial and tangential velocity components and it can be calculated following the approach proposed by Aphale et al. (2003). Miller (1996) indicated that for a spinning disc mechanism with a diameter of 600 mm and operating at a rotational speed of 750 rpm, the velocity of the particle at the instant it leaves the disc is in the order of 23.5 m s^{-1}. Studies into the particle motion off the spinning disc were conducted by Mennel and Reece (1963), Hofstee (1994), Miller (1996), Grift et al. (1997) and Aphale et al. (2003). The main physical properties of the material affecting fertiliser particle motion in the air are particle size and size distribution, particle density and aerodynamic resistance (Hofstee and Huisman, 1990; Miller, 1996). There are, however, interactions between the various physical properties of a fertiliser material which also affect its distribution performance; e.g. particle size, particle density and bulk density are interrelated; hence, they are likely to influence the distribution performance (Miller, 1996).

This chapter focuses on the study of some of the physical properties of the fertiliser materials used in 2010 in relation to the aerodynamic behaviour of individual fertiliser particles off-the-spinning disc. The analysis conducted herein assumes the use of a spinning disc fertiliser spreader which is common type in most arable situations (Dampney et al., 2003). In the following section (**Section 4.2**); a mathematical model is presented to aid predicting the point at which individual fertiliser particles leaving a spinning disc land on the soil. The analysis is based upon previous investigations reported in Mennel and Reece (1963), Miller (1996), Grift et al. (1997) and Parkin et al. (2005).

4.2 Fertiliser particle motion off the spinning disc

Nomenclature

α_0 = launch angle (rad);
d = particle diameter (m);
C_D = drag coefficient;
D = drag force [modulus] (N);
g = gravity acceleration [modulus] (m s^{-2});
m = mass (kg);
p = number of points in the integration interval;
R = radius particle (m);
Re = Reynolds number; $Re = \dfrac{\rho d v}{\mu}$
S = wet area (m^2);
t = time (s);
v = velocity of the particle (m s^{-1});
v_0 = initial velocity (m s^{-1}); velocity of the particle leaving the spinning disc.
Δt = time step (s);
ρ = density (kg m^{-3});
μ = dynamic viscosity of the air; (s m kg^{-1}).

Figure 4.1 shows the trajectory and the forces acting on a fertiliser particle launched from a height (h_0) with an angle (α_0) under conditions of still air with friction. These forces are proportional to the characteristics of the particle; most importantly, particle mass, wet area, drag coefficient, air density and instantaneous velocity (Grift et al., 1997). A simplification of the analysis is usually made by regarding the fertiliser particles as being spherical (symmetrical). Mennel and Reece (1963) stated that this is a reasonable assumption for most particle shapes that are likely to be distributed from a spinner spreader. When the particle is launched from a height (h_0) with velocity (v_0) and angle (α_0) immersed in air, it is subjected to the action of gravity (g) and drag force (D) that acts in the direction of the velocity and opposite to it. The trajectory and the forces acting on the fertiliser particle are shown in **Figure 4.1.**

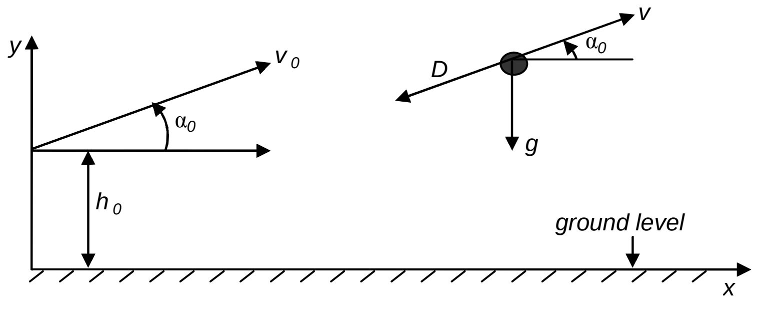


Figure 4.1: Trajectory (left) and forces (right) acting on a fertiliser particle.

Newton's momentum equation applied to the particle and projected on the parallel (x) and perpendicular (y) axes to the ground yields:

$$-D\cos\alpha = m\frac{d^2x}{dt^2} = m\ddot{x} \quad \textbf{[4.1]}$$

$$-D\sin\alpha - g = m\frac{d^2y}{dt^2} = m\ddot{y} \quad \textbf{[4.2]}$$

Also, the following cinematic equation applies:

$$\frac{dy}{dx} = \tan\alpha = \frac{dy}{dt}\frac{dt}{dx} = \frac{\dot{y}}{\dot{x}} \quad \textbf{[4.3]}$$

In aerodynamics, air drag is given by the following equation:

$$D = \frac{1}{2}\rho C_D S v^2 = \frac{1}{2}\rho C_D S\left(\dot{x}^2 + \dot{y}^2\right) \quad \textbf{[4.4]}$$

Since velocity *v* is given by:

$$v = \sqrt{\left(\dot{x}^2 + \dot{y}^2\right)} \quad \textbf{[4.5]}$$

The drag coefficient, C_D, is an empirical number which to a first order is a function of the shape of the particle and the Reynolds number, *Re*, which is given by:

$$Re = \frac{\rho d v}{\mu} = \frac{\rho d}{\mu}\sqrt{\left(\dot{x}^2 + \dot{y}^2\right)} \quad \textbf{[4.6]}$$

By replacing **[Equation 4.4]** in **[Equations 4.1** and **4.2]** and after some algebra the equation yields as follow:

$$\ddot{x} = -\frac{1}{2m}\rho C_D S\left(\dot{x}^2 + \dot{y}^2\right)\cos\left(a\tan\frac{\dot{y}}{\dot{x}}\right) \qquad \textbf{[4.7]}$$

Where:

$$C_D\left(\dot{x}, \dot{y}\right) \qquad \textbf{[4.8]}$$

And,

$$\ddot{y} = -\frac{1}{2m}\rho C_D S\left(\dot{x}^2 + \dot{y}^2\right)\sin\left(a\tan\frac{\dot{y}}{\dot{x}}\right) - \frac{g}{m} \qquad \textbf{[4.9]}$$

Where:

$$C_D\left(\dot{x}, \dot{y}\right) \qquad \textbf{[4.10]}$$

The system given in **[Equations 4.7** and **4.9]** is a non-linear system of second order differential equations. Subsequently, by introducing the following change of variables shown in **[Equations 4.11** and **4.12**], the system is reduced to a non-linear system of first order differential equations as shown in **[Equations 4.13** and **4.15]**:

$$\frac{dx}{dt} = \xi \qquad \textbf{[4.11]}$$

$$\frac{dy}{dt} = \eta \qquad \textbf{[4.12]}$$

Then,

$$\dot{\xi} = -\frac{1}{2m}\rho C_D S\left(\xi^2 + \eta^2\right)\cos\left(a\tan\frac{\eta}{\xi}\right) \qquad \textbf{[4.13]}$$

Where:

$$C_D\left(\xi,\eta\right) \quad \textbf{[4.14]}$$

And,

$$\dot{\eta} = -\frac{1}{2m}\rho C_D S\left(\xi^2+\eta^2\right)\sin\left(a\tan\frac{\eta}{\xi}\right)-\frac{g}{m} \quad \textbf{[4.15]}$$

Where:

$$C_D\left(\xi,\eta\right) \quad \textbf{[4.16]}$$

As stated earlier, the drag coefficient, C_D, can be expressed as a function of the Reynolds number, *Re*, and the shape of the particle as follow:

$$C_D = f\left\{Re, shape\right\} \quad \textbf{[4.17]}$$

Where:

$$Re = Re\left(\dot{x},\dot{y}\right) = Re\left(t\right) \quad \textbf{[4.18]}$$

Therefore,

$$C_D = f\left\{Re\left(\dot{x},\dot{y}\right), shape\right\} \quad \textbf{[4.19]}$$

The value of C_D is dependent on the air flow around the particle and the geometrical characteristics of the particle (Mennel and Reece, 1963). The characteristics of this flow and the ratio of the resulting drag force due to inertia and fluid's viscosity are described by the *Re* number (Mennel and Reece, 1963). The *Re* number as defined in **[Equation 4.6]** can be now expressed in the form shown in **[Equation 4.20]**:

$$Re = \frac{\rho 2Rv}{\mu} = \frac{\rho 2R}{\mu}\sqrt{\left(\xi^2+\eta^2\right)} \quad \textbf{[4.20]}$$

In this analysis, a value of air density of 1.225 kg m^{-3} was used and it corresponds to the density of the air at 15°C. The relationship between C_D and *Re* is complex (Mennel and Reece, 1963). For small particles which move slowly Stokes' Law applies whereas for large particles which move at higher velocities Newton's Law applies (Miller and Parkin, 2005; Parkin et al., 2005). There is also a transition zone defined for values of *Re* between 1 and 1000 where the calculation of C_D is difficult with a simple equation (Parkin et al., 2005). Parkin et al. (2005) based upon the procedure reported in Douglas et al. (1995) regarded the C_D as being constant at 0.44 for $Re > 500$ (turbulent flow); $C_D = 18.5 \times Re^{-0.6}$ for *Re* between 0.2 and 500 (transition from turbulent to laminar flow); and $C_D = 24 \times Re^{-1}$ for $Re < 0.2$ (laminar flow). The relationship between C_D and *Re* for spherical fertiliser particles is shown graphically in **Appendix A.4.4** (after, Parkin et al., 2005).

Mennel and Reece (1963), who also used a similar scheme for the calculation of C_D, stated that laminar flow is unlikely to occur in most fertiliser particle-distribution situations. In addition, Grift et al. (1997), based on the work of von-Zabeltitz (1967), regarded C_D as being constant for small distance intervals in the trajectory of the particle and calculated C_D according to the *Re* number encountered in each interval. The work of Aphale et al. (2003) also assumed a constant C_D over the range of *Re* numbers encountered by the particle. Walker et al. (1997) following the studies of Hofstee (1993) and Grift et al. (1997) highlighted that the use of a constant C_D, as supposed to a recursive time step solution in which C_D varies with velocity, can bring about errors, especially for small and low density fertiliser particles.

The particle trajectory model presented herein uses a C_D which is calculated for every instant in the particle's trajectory as a function of the *Re* number **[Equation 4.19]**. The value of *Re* is not constant as it depends on the velocity of the particle **[Equations 4.6** and **4.20]** which also changes over time in the particle's trajectory **[Equation 4.18]**. **Equations [4.13** and **4.15]** can be solved by imposing the initial velocity and the angle at which the particle is launched as boundary conditions:

$$\xi(t=0) = v_0 \cos\alpha_0 \qquad \textbf{[4.21]}$$

And,

$$\eta(t=0) = v_0 \sin\alpha_0 \qquad \textbf{[4.22]}$$

Equations [4.13 and **4.15]** are coupled and do not admit primitives in terms of elementary functions. A convenient method to solve the system is by employing a numerical scheme and a relatively simple procedure involves the use of the *Euler* scheme which is convergent and zero-stable for sufficiently small time steps, Δt. The proposed scheme produces the solution for the instant $(n+1)$ from the solution in the previous instant (t).

Therefore,

$$t^{n+1} = t^n + \Delta t \qquad \textbf{[4.23]}$$

The general form of the scheme is shown below:

$$u^{n+1} = u^n + \Delta t F^n \qquad \textbf{[4.24]}$$

For a differential equation in the form of:

$$\frac{du}{dt} = F(u,t) \qquad \textbf{[4.25]}$$

For this particular system of equations, the solution in the instant $(n+1)$ is given by:

$$\xi^{n+1} = \xi^n - \Delta t\left(\frac{1}{2m}\rho C_D^n S\left(\left(\xi^n\right)^2 + \left(\eta^n\right)^2\right)\cos\left(a\tan\frac{\eta^n}{\xi^n}\right)\right) \qquad \textbf{[4.26]}$$

And,

$$\eta^{n+1} = \eta^n - \Delta t\left(\frac{1}{2m}\rho C_D^n S\left(\left(\xi^n\right)^2 + \left(\eta^n\right)^2\right)\sin\left(a\tan\frac{\eta^n}{\xi^n}\right) - \frac{g}{m}\right) \qquad \textbf{[4.27]}$$

Equations [4.26 and **4.27]** provide the velocity field which must be integrated again in order to obtain the trajectory of the particle. Due to the velocity field (ξ) and (η) being expressed in a discrete form, it is also necessary to conduct the integration numerically.

A convenient method of numerical integration is the trapezoid rule which is given in its general form by:

$$\int_a^b f(x)dx \approx \frac{b-a}{p}\left[\frac{f(a)+f(b)}{2}+\sum_{k=1}^{p-1} f\left(a+k\frac{b-a}{p}\right)\right] \quad \textbf{[4.28]}$$

Then, when applied to the problem under study, ξ and η are integrated as follow:

$$x=\int_0^t \xi dt \approx \frac{t}{p}\left[\frac{\xi(t=0)+\xi(t=t)}{2}+\sum_{k=1}^{p-1}\xi\left(k\frac{t}{p}\right)\right] \quad \textbf{[4.29]}$$

And,

$$y=\int_0^t \eta dt \approx \frac{t}{p}\left[\frac{\eta(t=0)+\eta(t=t)}{2}+\sum_{k=1}^{p-1}\eta\left(k\frac{t}{p}\right)\right] \quad \textbf{[4.30]}$$

The proposed particle trajectory model was used to predict the stop distance; that is, the distance measured from the edge of a spinning disc to the landing point of the particle on the soil, of individual fertiliser particles when they are spread using a spinning disc fertiliser spreader. Olieslagers et al. (1996) and later Grift et al. (1997) suggested that the predicted point of landing of individual fertiliser particles can be accumulated to produce a spread pattern.

Equations [4.1-4.30] were solved using FORTRAN (2003). The landing distances were calculated for individual particles of urea, OMF_{15}, OMF_{10} and biosolids granules based on the physical properties of the materials supplied in 2010; these were reported in **Chapter 3**. The analysis was conducted using a range of values of initial velocities (v_0) available in the literature (Miller, 1996; Parkin et al., 2005). Hence, the factors affecting this initial velocity such as the flow rate, coefficient of friction, geometry of the vane, number of vanes on the disc, disc radius, and rotational velocity of the disc (Hofstee, 1995; Grift et al., 2006) were not considered in this analysis.

The model was first used to calculate the landing distance for the mean particle density and median particle diameter (D_{50}) given a constant height above the ground (h_0) and varying either the launch angle (α_0) or the initial velocity (v_0).

A second analysis calculated the landing distance of the particles but the angle of projection remained unchanged $(\alpha_0 = 0^\circ)$ and the particle diameter and the initial velocity were variable. In addition, and based on the approach of Parkin et al. (2005), the relationship between initial velocity, launch angle, particle diameter (d) and particle density (ρ_p) were explored further for a fixed height above the ground so that the landing distance of individual fertiliser particles can be estimated for a range of conditions.

From the above, it is possible to estimate the landing distance of individual fertiliser particles according to the characteristics of the material; i.e. particle density and particle diameter, and also in relation to the characteristics of the spreading mechanism; i.e. initial velocity of the particle leaving the spinning disc and launch angle. Therefore, for a given fertiliser material, it may be possible to use the information reported to adjust the spreading equipment in order to achieve the required spreading width. Conversely, the fertiliser material (in terms of its particle size range and particle density) can be selected to achieve the required spreading width with the available spreading equipment. As highlighted above, the value of h_0 (height above the ground) was maintained constant at 1 m from the ground level. The analysis presented here differs from that of Parkin et al. (2005) in that the C_D was calculated for every instant in the particle's trajectory as a function of the *Re* number **[Equation 4.19]**; whereas in the previous study (Parkin et al., 2005) C_D was calculated based on the method mentioned earlier (Douglas et al., 1995).

Table 4.1 summarises the parameters used in the analysis as determined for each of the fertiliser materials supplied in 2010. **Table 4.2** shows the range of values of initial velocity, launch angle, particle diameter and density, and height above the ground used in the model. The results obtained are presented in **Section 4.3**.

Table 4.1: Physical properties of 2010's fertiliser materials used in the model (for particle density n=100).

2010	-------------------- **Fertiliser material** ---------------------				
Parameter	**Urea**	**OMF_{15}**	**OMF_{10}**	**Biosolids granules**	**Unit**
D_{50}	3.03	4.79	3.25	2.21	(mm)
Particle density (ρ_p)	1432	1357	1297	1333	(kg m^{-3})

Table 4.2: Range of values of selected parameters used in the analyses to predict the landing distance of individual fertiliser particles.

Parameter	Value (or range)	Unit
Initial velocity (v_0)	5 – 50	(m s^{-1})
Launch angle (α_0)	0 – 50	(degrees)
Particle diameter (d)	1.00 – 5.50	(mm)
Particle density (ρ_p)	1250 – 1500	(kg m^{-3})
Height above the ground (h_0)	1.00	(m)

4.3 Results and discussion

The results obtained from the particle trajectory model are shown in **Figures 4.2** and **4.3**. The numerical results from which these graphs were drawn are provided tables in **Appendix A.4.1**.

As can be seen from the graphs, the maximum landing distance is achieved with launch angles in the range of 20 to 30 degrees for all materials. In addition, for a given initial velocity and angle, the landing distance is increased when the particle diameter is increased. For example, the landing distance of OMF_{15} for a given initial velocity and angle is comparatively higher than that estimated for biosolids granules which has a particle density of similar order of magnitude (although smaller) but its D_{50} value is considerably smaller. It appears that the effect of the particle density in increasing the landing distance of the particle is relatively smaller compared with that of the particle diameter.

As reference, and based on data reported in the literature for mineral fertilisers, it is reasonable to state that fertiliser particles can be released from a spinning disc with velocities in the range of 20 to 40 m s^{-1} but this is very dependent on numerous factors and it should be treated as guidance only. However, if particles are released at that range of initial velocities and with angles of 20 to 30 degrees, up to 50% of the particles in the fertiliser samples used in this research are expected to land at distances ranging between 6.80 and 8.70 m (biosolids), 8.90 and 11.80 m (OMF_{10}), 11.80 and 16.10 m (OMF_{15}) and 9.10 and 11.90 m (urea). This suggests that it may not be possible to operate at tramlines wider than 18 m spacing but this will depend on the required overlapping, the shape of the spreading pattern and the machinery settings. An exception could be OMF_{15} but it is possible that the quality of the material will prevent from working at wider tramlines (wide range of particle sizes and high GSI – see **Chapter 3**).

Given the specific conditions shown in **Figure 4.3** and for the range of initial velocities mentioned earlier this statement appears to be reasonable (landing distances ≤12 m in all materials).

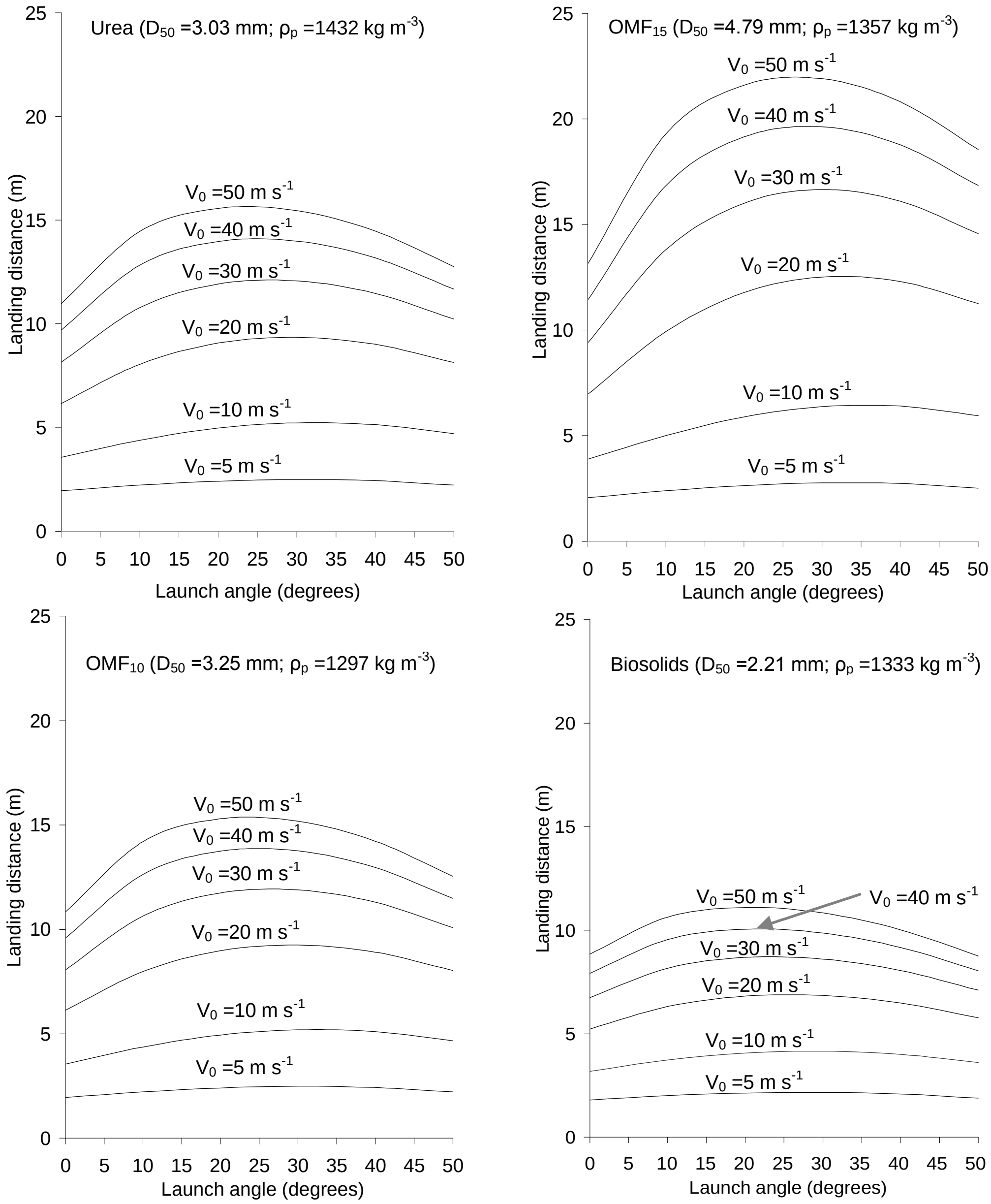


Figure 4.2: Calculated landing distances as a function of the launch angle for increasing initial velocity for urea, OMF$_{15}$, OMF$_{10}$ and biosolids granules (2010). Particle diameters equivalent to D$_{50}$ and particle densities corresponding to the mean value for the material [assumes h_0 =1 m].

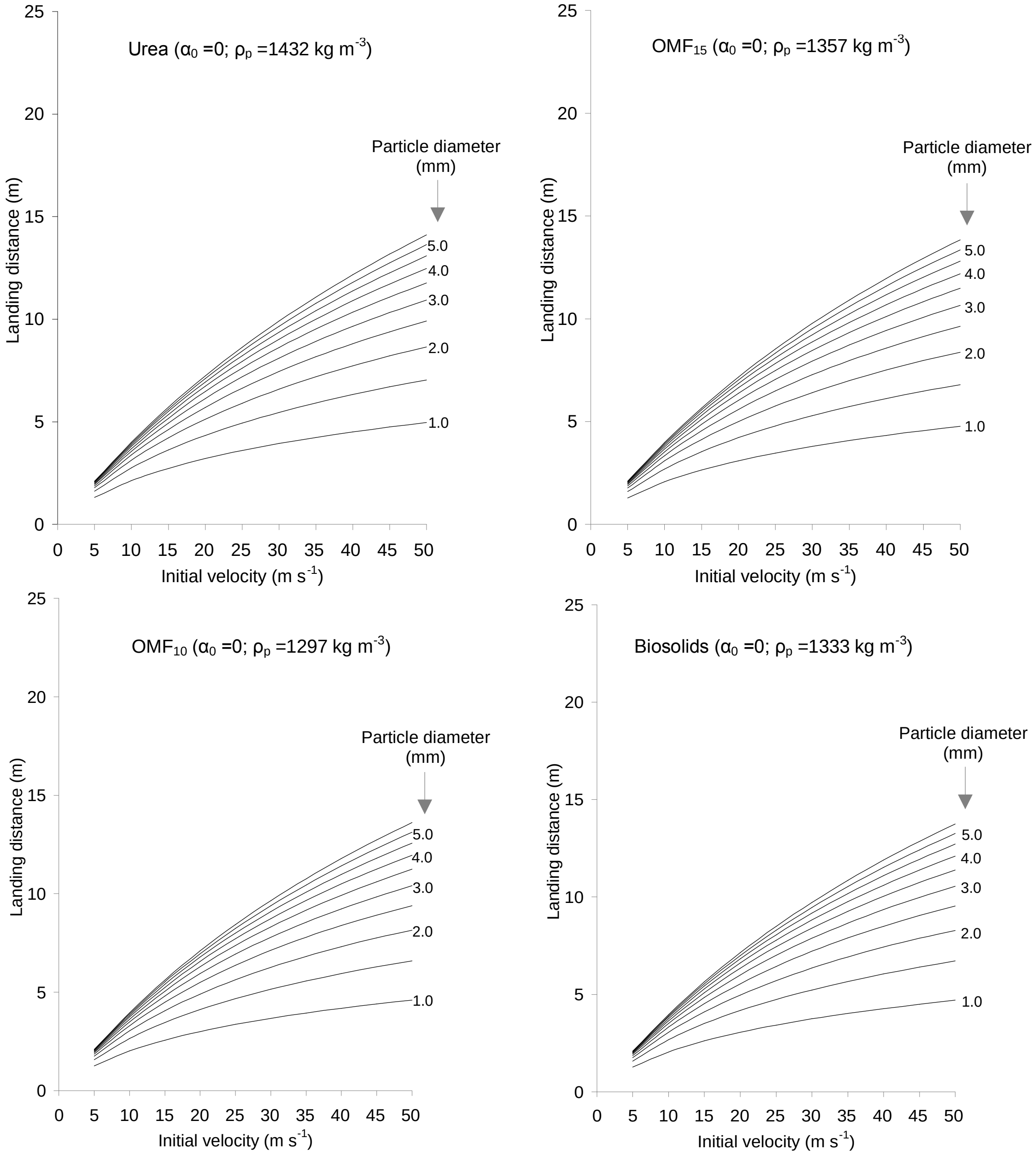


Figure 4.3: Calculated landing distances as a function of the initial velocity for urea, OMF$_{15}$, OMF$_{10}$ and biosolids granules (2010) for increasing particle diameters. Particle densities corresponding to the mean value for the material [assumes h_0 =1 m].

As reported in **Chapter 3**, the fertiliser samples in 2010 showed D_{84} values of 4.40 mm for OMF$_{10}$ and 7.10 mm for OMF$_{15}$; therefore, for OMF$_{10}$ the majority of the particles would land at distances $\leq$16.0 m which is approximately the distance calculated for OMF$_{15}$ for the range of particle velocities and launch angles given above (acknowledging the differences in particle density between both materials).

For OMF_{15} the D_{84} value falls outside the range of diameters estimated with the model for which it is expected that a significant proportion of the particles will land at farther distances. As shown in **Chapter 3**, approximately 75% of the particle in OMF_{15} were ≤5.50 mm; these will land at distances of approximately 10.5 m to 18.2 m (for $\alpha_0 = 10^\circ$ and $v_0 = 20 - 40$ m s^{-1}). For all materials (except for urea which showed a relatively lower GSI value), the uniformity of distribution is likely to be affected by the large differences encountered in the range of particle diameters (**Table 3.16**). This is likely to produce, initially, a narrower spreading width (as smaller particles would be first released from the disc) and then to widen up progressively as larger particles reach the disc during spreading resulting in an inconsistent particle distribution pattern along the tramline. The information presented in **Figure 4.3** shows the relationship between the increase in the initial velocity and the landing distance for increasing particle diameters. These were calculated for $\alpha_0 = 0^\circ$ and the particle densities corresponding to the materials. It can be seen that, for a given velocity, the particle will travel farther as its diameter is increased, which is expected.

As highlighted earlier, and based on the studies of Parkin et al. (2005), the trajectory particle model was used to produce the information presented in **Tables 4.3** and **4.4**. These show the effect of the relationship between particle diameter and particle density on the landing distance of the particles. These were calculated for $\alpha_0 = 0^\circ$ and $\alpha_0 = 10^\circ$ and $v_0 = 20 - 40$ m s^{-1}. It can be seen from the tables that an increase in particle diameter from 3 mm to 4 mm results in approximately 10% to 14% increase in the landing distance for $\alpha_0 = 0^\circ$ and between 16% and 23% increase for $\alpha_0 = 10^\circ$. Parkin et al. (2005) found that a 30% reduction in particle density (e.g. from ammonium nitrate to urea) resulted in 14% decrease in the landing distance whereas an increase in the particle size from 2.2 mm to 3.2 mm increased the landing distance by *c*.19% for $v_0 = 20$ m s^{-1}. In general, the landing distances shown in the table appear to be in agreement to those reported by Parkin et al. (2005) for the range of particle sizes and particles densities investigated but comparisons are limited between the two studies as their study does not provide a reference to the launch angle of the particles used for the calculation of the landing distances. Their study emphasises that although detailed performance and distribution cannot be predicted from basic parameters; i.e. particle size and density, it is possible to provide broad indications of the likely performance.

Table 4.3: Calculated landing distances from the particle trajectory model for $\alpha_0 = 0^\circ$ and a range of initial velocities, particle diameters, and particle densities [h_0 =1 m].

$\alpha_0 = 0^\circ$	------------------------ Landing distance (m) ------------------------					
$v_0 = 20$ m s^{-1}	Particle density (kg m^{-3})					
Particle diameter (mm)	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**
1.0	2.92	3.00	3.08	3.16	3.24	3.31
1.5	4.03	4.12	4.20	4.29	4.37	4.44
2.0	4.82	4.91	4.99	5.07	5.15	5.23
2.5	5.41	5.49	5.57	5.65	5.73	5.80
3.0	5.86	5.95	6.02	6.10	6.17	6.23
3.5	6.22	6.30	6.37	6.44	6.50	6.56
4.0	6.50	6.57	6.64	6.70	6.76	6.82
4.5	6.72	6.78	6.84	6.90	6.96	7.01
5.0	6.89	6.96	7.01	7.07	7.12	7.17
5.5	7.04	7.10	7.16	7.21	7.26	7.31

$\alpha_0 = 0^\circ$	------------------------ Landing distance (m) ------------------------					
$v_0 = 30$ m s^{-1}	Particle density (kg m^{-3})					
Particle diameter (mm)	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**
1.0	3.57	3.68	3.78	3.88	3.98	4.08
1.5	5.03	5.15	5.27	5.39	5.50	5.61
2.0	6.14	6.27	6.39	6.51	6.63	6.75
2.5	7.00	7.13	7.26	7.38	7.50	7.61
3.0	7.67	7.80	7.92	8.04	8.15	8.26
3.5	8.20	8.32	8.44	8.55	8.66	8.76
4.0	8.63	8.75	8.86	8.97	9.07	9.17
4.5	8.98	9.10	9.20	9.31	9.41	9.50
5.0	9.29	9.39	9.50	9.60	9.69	9.78
5.5	9.55	9.66	9.76	9.85	9.94	10.03

$\alpha_0 = 0^\circ$	------------------------ Landing distance (m) ------------------------					
$v_0 = 40$ m s^{-1}	Particle density (kg m^{-3})					
Particle diameter (mm)	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**
1.0	4.06	4.19	4.31	4.43	4.55	4.66
1.5	5.80	5.95	6.10	6.24	6.38	6.52
2.0	7.16	7.32	7.48	7.64	7.79	7.93
2.5	8.22	8.39	8.56	8.71	8.87	9.02
3.0	9.07	9.24	9.40	9.56	9.71	9.86
3.5	9.76	9.93	10.09	10.24	10.39	10.53
4.0	10.34	10.50	10.66	10.81	10.95	11.09
4.5	10.83	10.99	11.14	11.29	11.43	11.57
5.0	11.26	11.42	11.57	11.71	11.85	11.98
5.5	11.64	11.79	11.94	12.08	12.22	12.35

Table 4.4: Calculated landing distances from the particle trajectory model for $\alpha_0 = 10^\circ$ and a range of initial velocities, particle diameters, and particle densities [h_0 =1 m].

$\alpha_0 = 10^\circ$	------------------------ **Landing distance (m)** ------------------------					
$v_0 = 20$ m s^{-1}	**Particle density (kg m^{-3})**					
Particle diameter (mm)	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**
1.0	3.07	3.16	3.26	3.35	3.44	3.53
1.5	4.49	4.61	4.73	4.85	4.96	5.07
2.0	5.65	5.79	5.92	6.05	6.18	6.31
2.5	6.62	6.77	6.92	7.06	7.19	7.33
3.0	7.46	7.61	7.77	7.91	8.05	8.19
3.5	8.18	8.34	8.49	8.64	8.79	8.93
4.0	8.79	8.95	9.11	9.26	9.41	9.55
4.5	9.32	9.48	9.63	9.78	9.93	10.07
5.0	9.77	9.93	10.09	10.23	10.38	10.51
5.5	10.17	10.33	10.48	10.63	10.77	10.90
$\alpha_0 = 10^\circ$	------------------------ **Landing distance (m)** ------------------------					
$v_0 = 30$ m s^{-1}	**Particle density (kg m^{-3})**					
Particle diameter (mm)	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**
1.0	3.74	3.86	3.99	4.11	4.23	4.34
1.5	5.59	5.76	5.92	6.08	6.24	6.40
2.0	7.20	7.40	7.59	7.79	7.98	8.16
2.5	8.61	8.83	9.06	9.27	9.48	9.69
3.0	9.84	10.09	10.33	10.56	10.79	11.01
3.5	10.93	11.19	11.44	11.69	11.93	12.16
4.0	11.89	12.16	12.42	12.68	12.93	13.17
4.5	12.75	13.03	13.30	13.56	13.82	14.07
5.0	13.52	13.81	14.08	14.35	14.61	14.87
5.5	14.23	14.52	14.80	15.07	15.34	15.59
$\alpha_0 = 10^\circ$	------------------------ **Landing distance (m)** ------------------------					
$v_0 = 40$ m s^{-1}	**Particle density (kg m^{-3})**					
Particle diameter (mm)	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**
1.0	4.25	4.39	4.53	4.68	4.82	4.96
1.5	6.43	6.63	6.83	7.02	7.22	7.41
2.0	8.36	8.61	8.86	9.10	9.33	9.57
2.5	10.08	10.36	10.65	10.92	11.19	11.46
3.0	11.61	11.93	12.24	12.54	12.84	13.14
3.5	12.99	13.34	13.67	14.00	14.32	14.64
4.0	14.25	14.61	14.97	15.31	15.65	15.99
4.5	15.39	15.77	16.15	16.51	16.87	17.21
5.0	16.45	16.84	17.23	17.61	17.98	18.34
5.5	17.43	17.84	18.24	18.63	19.01	19.38

The particle size range of OMF required to match the landing distance of urea can be estimated by interpolation from the values given in the tables according to the specified spreading conditions. It results that for OMF_{15} and OMF_{10}, the required particle size range to match the minimum and maximum landing distance of urea (particle size ranging from 1.00 to 5.00 mm) would be (approximately) 1.05 and 5.30 mm and 1.10 and 5.50 mm respectively. This is a mere indication based on the results of the model and it should be verified experimentally.

4.4 Spreading of OMF_{15} using a pneumatic fertiliser spreader at United Utilities plc experimental site in Broxton (Cheshire, UK)

4.4.1 Introduction

In February 2009, United Utilities plc established an experimental site at Fields Farm in Broxton (Cheshire, CH3 9JR, UK) which is used for demonstration purposes to the public. At the site, OMF products are tested on arable and grass crops using larger plots (dimensions $24 \times 140 \ m$) than those of the College Farm at Silsoe.

Farm machinery manufacturers often provide relatively accurate indications of fertiliser flows (i.e. fertiliser passing through the hopper) but there is usually lack of information regarding fertiliser distribution across the working width of spreading equipment (Weiser, 2002). Indeed, no information was available on the likely distribution uniformity for the type of fertilisers used in this research, except for urea. Hence, prior to the application of the fertilisers (OMF) to the demonstration plots, a simple spreading test was conducted with OMF_{15} using a pneumatic fertiliser spreader. The aim of the test was to provide an indication of the spreading behaviour of the product and to know whether adjustments on the equipment were needed prior to the fertiliser application on the experimental plots. Pneumatic applicators are generally simpler to calibrate compared with the spinning discs type but positioning of the equipment is more critical because overlapping is not needed between two adjacent bouts (Moller and Svenssen, 1991). The method employed and the results obtained during the exercise are presented in the following sections.

4.4.2 Materials and method

The test was conducted in accordance with the guidelines given in ASAE standards: ASAE-S341.4 (ASAE, 1999) using a pneumatic fertiliser spreader Kuhn 2212 (**Figure 4.4**).

Figure 4.4: A picture showing the pneumatic spreading equipment used for the test.

The equipment was loaded with the OMF_{15} produced in 2009 to approximately 70-75% of its capacity (the capacity of the hopper was *c*.2000 litres) and the tractor was driven at 5 miles per hour in accordance with the standards. Due to the limited number of trays available for the trial, instead of using the full width of the machine only one boom was operated. This enabled taking three measurements by placing 3 sets of 9 collecting trays of $0.25\ m^2$ each (dimensions $0.5 \times 0.5 \times 0.15\ m$) across the operated working width of the spreader; the trays are shown in **Figure 4.5**.

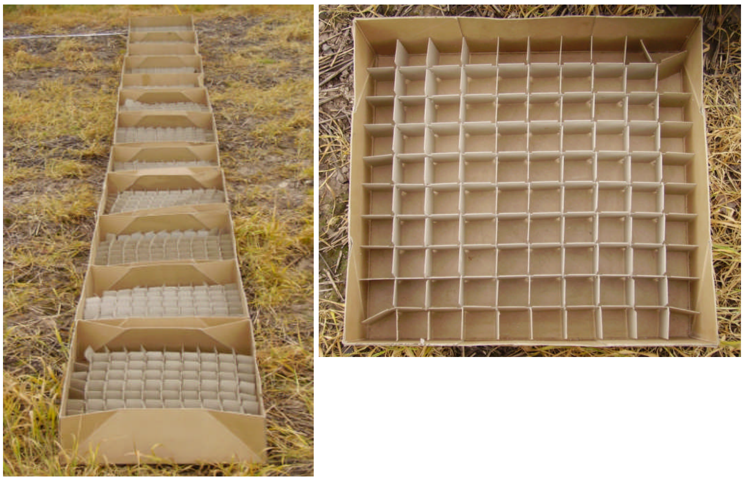


Figure 4.5: A picture showing a set of collecting trays (left) and close-up of a tray (right).

Each set of trays was placed perpendicular to the direction of travel at 10 m apart from each other and the boom of the spreader was driven over the trays. Subsequently, the fertiliser deposited in the trays was collected and weighted, and the weight recorded individually for each tray. A statistical analysis (ANOVA) was undertaken to determine if there were significant differences in the amount of fertiliser collected in each individual tray. The least significant differences were used to compare the means ($LSD_{[5\%\ level]}$). This is presented in **Appendix A.4.2**.

The uniformity of distribution was expressed by means of the coefficient of variation (CV) in the weight of the fertiliser recorded for each tray. No significant effect of wind was recorded during the test.

4.4.3 Results and discussion

Figure 4.6 shows the weight of the fertiliser collected in the trays as a function of the position of the trays across the measured working width of the machine. The statistical analysis showed that there were not significant differences (p=0.572) in the amount of fertiliser collected in each tray. This means that, overall, the fertiliser was spread uniformly across (half) the working width of the applicator.

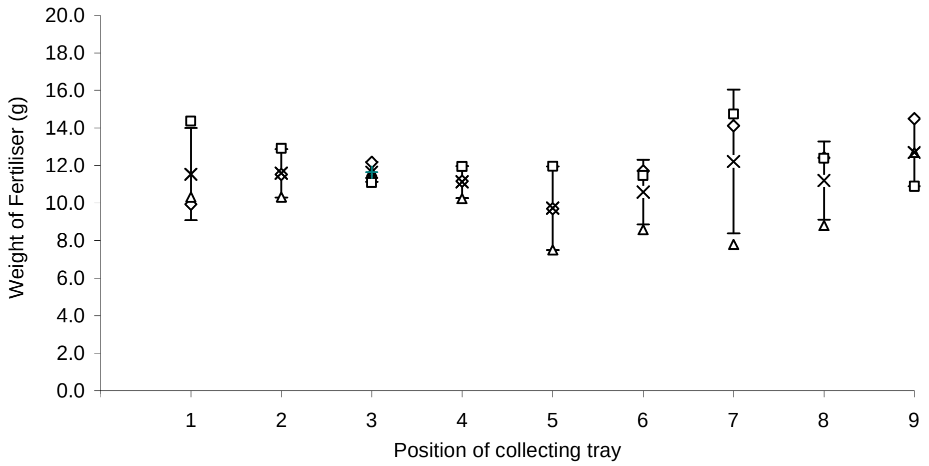


Figure 4.6: Weight of the fertiliser collected in individual trays in relation to their position across the spreading width of the equipment (LSD$_{[5\%\ level]}$ =2.82). The value indicated with (×) corresponds to the mean value for the 3 observations made in each position. The vertical bars indicate the *SD* of the mean for each position.

The coefficient of variation (CV) indicates, in percentages terms, how evenly a fertiliser material is spread (Roberts, 2000). It is usually acknowledged that a CV ≤10% means that the equipment is working with relatively high accuracy but CV values of up to 15% are acceptable. Values of CV above 15% indicate that the equipment needs attention and therefore maintenance work is required. Previous studies (England and Audsley, 1987; Miller, 1996) demonstrated that high values of CV are related to financial losses. These could be associated with the reduction in crop yield as a result of uneven fertiliser application/distribution and it is usually acknowledged that for values of CV in excess of 18% financial losses can be significant. For a first wheat crop, the financial loss can be as high as £7.45 per hectare if CV is 20% assuming a selling price for the crop of £110 per tonne (England and Audsley, 1987; Miller, 1996).

The coefficient of variation was found to be acceptable (CV =12.4%) despite that a recent maintenance service had been conducted on the equipment. This led to the conclusion that the value encountered was mainly due to the relatively low physical quality of the fertiliser used and to a lesser extent to the state of the equipment. The particle size distribution (**Chapter 3**) showed that approximately 4.5% of particles were smaller than 1.18 mm in diameter. It is possible that the clods of urea present in the material were responsible for increasing the proportion of fine particles during spreading following disintegration in the hopper. Particles smaller than 1 mm in diameter are generally responsible for the increase in the coefficient of variation during spreading (Hofstee and Huisman, 1990). The presence of fine particles was also evident during the application of the product as can be seen from **Figure 4.7**.

Figure 4.7: Application of OMF_{15} on the demonstration on the plots at the experimental site in Broxton, Cheshire.

Although the weight of the fertiliser collected in each individual tray was not significantly different from each other it was important to determine possible reasons for the small differences recorded. Hence, the weight of the fertiliser collected in the trays was regressed against the position of the tray to identify if there was a correlation between the two parameters. The regression analysis (**Figure 4.8** and **Appendix A.4.2**) showed that the correlation between the two variables was nonsignificant (p=0.643). Therefore, the differences recorded in the weight of the fertiliser collected in each tray could not be explained by the position of the tray. This was an indication that these variations were mainly due to the physical quality of the fertiliser; i.e. particle size and size distribution, which affected the flowability of the material through the hopper, the boom and also inside the boom.

The weight of the fertiliser collected in the trays was converted to kg [N] ha^{-1} to provide an indication of the pattern of distribution of nitrogen in the field for every 0.5 m strip (**Figure 4.9**). Under these operating conditions, the fertiliser was applied at a rate equivalent to 454.8 kg [OMF$_{15}$] ha^{-1}. The nitrogen concentration of OMF$_{15}$ produced in 2009 was 13.96% (w w^{-1}) which therefore gives a mean nitrogen application rate equivalent to 63.5 kg [N] ha^{-1}.

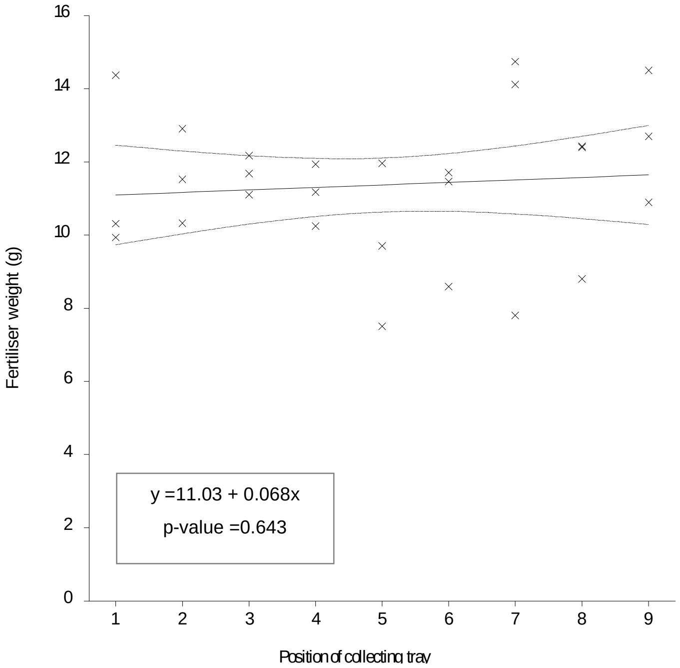


Figure 4.8: Regression analysis to show the relationship between the position of the collecting tray and the weight of the fertiliser encountered in individual tray [Fitted (solid line) and observed data (×), and 95% confidence interval for the linear model (dotted lines)].

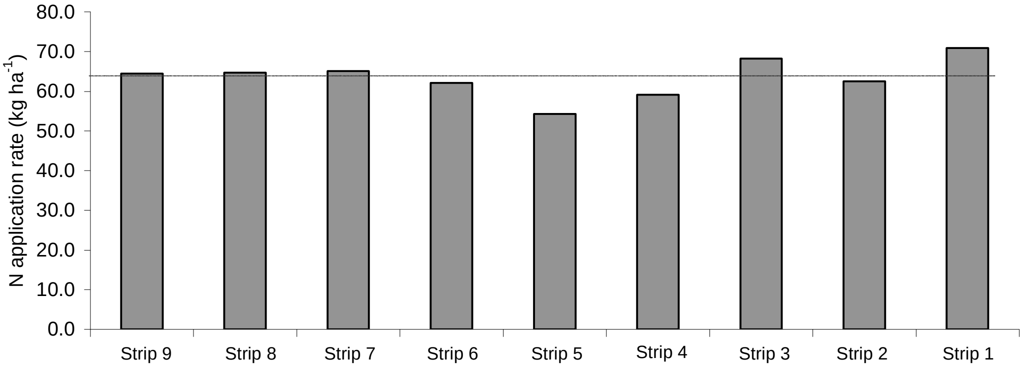


Figure 4.9: Pattern of distribution of nitrogen and application rate of nitrogen for individual field strips of 0.5 m wide. [The horizontal line indicates the mean nitrogen application rate equivalent to 63.5 kg [N] ha^{-1}; *SD* =4.90].

4.4.4 Summary spreading test

- The spreading test conducted provided basic information concerning the spreading characteristics of OMF_{15}. It appears that pneumatic fertiliser applicators can be satisfactorily used for the spreading of OMF despite the moderately high value of CV encountered (12.4%).
- A key aspect concerning the quality of the product is with regards to the improvement of its physical characteristics. It is important to maintain the proportion of fine particles (<1 mm) to a minimum as this fraction can be responsible for the increase in the value of CV which appeared to be the case in this test. The increase in the CV above a target range of 5% to 10% for field-conditions is likely to have a knock-on effect on fertiliser use efficiency and crop yield, and it could result in financial losses.

4.5 Conclusions

- It appeared from the trajectory model and based on the characteristics of the materials tested, that the spreading of OMF and biosolids granules with a spinning disc fertiliser spreader may not be possible to perform for tramlines wider than 12 to 18 m apart depending on the machinery settings and the required overlapping between two adjacent bouts.
- For the range of initial velocities investigated (20 to 40 $m\ s^{-1}$), the required range of particle size for OMF_{15} should be approximately between 1.05 mm and 5.30 mm in order to match, respectively, the minimum and maximum landing distances of urea with a particle size in the range of 1.00 mm to 5.00 mm. For OMF_{10} this range should be approximately between 1.10 mm and 5.50 mm in diameter respectively. However, this should be verified experimentally. Maximum landing distances were achieved with launch angles in the range of 20 to 30 degrees for all fertiliser materials.
- Due to the significant effect that particle diameter has upon the landing distance of individual fertiliser particles, special attention should be paid to producing the correct particle size distribution for the spreading equipment. The relationship between particle diameter and particle density reported in Chapter 3 may be taken into consideration when selecting the particle size range.
- From the above, a narrower particle size range would be preferable to a wider one. It is advisable to lower the values of GSI reported in Chapter 3 (≤15%) in order to minimise the effect of segregation which can affect the uniformity of distribution in the direction of travel while spreading.

- The proposed trajectory model appears to be a useful tool for estimating the landing distance of individual fertiliser particles. Validation of the model against experimental data is needed.

CHAPTER 5

SOIL INCUBATION STUDIES

5 SOIL INCUBATION STUDIES

5.1 Introduction

Soil incubation has been extensively used as a technique for the assessment of nitrogen availability from organic-based materials with the potential for application in crop production (e.g. Hamence, 1950; Bremmer and Shaw, 1957; Parker and Sommers, 1983; Chescheir et al., 1986; Smith et al., 1998; Cordovil, 2003; Cordovil et al., 2005). Garau et al. (1986) highlighted that a disadvantage of this method is that the occurrence of large concentrations of inorganic-N in non-leached systems can disrupt the mineralisation process and therefore underestimate the potentially mineralisable N content of an organic amendment. In this respect, high concentrations of $NH_4^+ - N$ (e.g. in excess of 400 mg $[NH_4^+ - N]$ kg^{-1}) can inhibit nitrification (McIntosh and Frederick, 1958; Smith et al., 1998). Fangueiro et al. (2008) based on the work of Lober and Reeder (1993) used an anaerobic incubation technique to determine the potential N mineralisation of fresh slurry samples. Due to the particular conditions of their experiment, the nitrogen balance was estimated on the basis of the $NH_4^+ - N$ in the system. The OMF products were formulated for application in grassland as well as arable cropping as discussed in **Chapter 3**. The mineral-N fraction (urea-N) is expected to be released and become available to the crop soon after application whereas the organic-N fraction (biosolid-N) is expected to release nitrogen progressively throughout the crop growing season and at a slower rate. The need for a better understanding of the nitrogen release characteristics following the soil application of organic materials to the soil had been indicated in earlier studies (e.g. Serna and Pomares, 1992; Bowden and Hann, 1997; Cordovil et al., 2007). This work was conducted in two stages. Initially, the purpose of the incubation studies was to identify how the two nitrogen fractions present in the OMF; i.e. inorganic- and organic-N, were released and became available for uptake by the crop. It also tried to identify whether the amount of nitrogen available in the soil could potentially match crop requirement, acknowledging the scale and the general conditions of the experiment. At a second stage, the work focused on the study of phosphorus and it had a similar aim which was to determine the release characteristics of phosphorus following application of OMF to the soil. A crucial aspect at this stage was to determine whether soil P-index was affected by OMF application also acknowledging the experimental conditions. The information coming from these studies will contribute to the understanding of nutrients availability following soil application of OMF under controlled laboratory conditions.

Efforts will be made to link the results obtained in this series of incubation studies with those of the field studies (**Chapters 7**). This will enable to connect the various experimental scales used in this research. The development of a strategy for the application of OMF will also benefit from the results reported in this Chapter. The objectives of the incubation studies are summarised below:

- To determine the release characteristics of OMF_{15} nitrogen and phosphorus under controlled laboratory conditions of soil moisture content and temperature, and
- To determine the effect of the soil application of OMF_{15} on soil P-index under controlled laboratory conditions.

5.2 Methodology

5.2.1 Description of the soils

The experiment used two soil types which were a sandy loam soil – Cottenham series, and a clay loam soil – Holdenby series (King, 1969). The soils were collected from Avenue and Showground Fields respectively at the College Farm at Silsoe. They corresponded to the same soil types used in the glasshouse studies (**Chapter 6**) and also for the sandy loam soil, to that of the field studies conducted in Avenue Field (**Chapter 8**). The soils were collected from the top 300 mm. Both sites were under arable cropping and they have had similar crop rotations and fertilisation regimes (see **Table 7.1**). A hand assessment of the particle size (Hodgson, 1997) was first conducted on a number of soil samples to aid selecting the appropriate soil types for the experiment. Research (Hodgson et al., 1976) has shown that good estimates of silt and clay contents can be obtained by means of the hand assessment method. The samples were subsequently analysed using the pipette method (Avery and Bascomb, 1974; BS 1377 Part 2.0, 1990) to confirm that preselected samples had the desired particle size range. The soils collected from the field were first air-dried and subsequently ground to pass a 2 mm sieve. Since the soils were maintained between 75% of field capacity and field capacity throughout the experiment, a determination of the moisture content corresponding to this point was needed. The method used was based on Avery and Bascomb (1974) and BS 7755 Section 5.5 (1999). Field capacity was measured in the laboratory by applying a suction of 0.05 bar (50 cm) to a sample of saturated soil, allowing it to come to equilibrium and subsequently measuring the water content of the sample. The results of the textural analysis, moisture content (%, mass basis) corresponding to field capacity and the bulk density values encountered for the soil in the natural state are shown in **Table 5.1**. These bulk density values were used as reference to calculate the amount of fertiliser required for each incubation pot assuming a soil depth of 0.2 m.

Table 5.1: Textural analysis, field capacity and soil bulk density for the two soils used in the incubation studies.

Determination (Soil depth 0 – 300 mm)	Soil type	
Textural analysis	**Clay loam**	**Sandy loam**
% Sand	46	67
% Clay	25	13
% Silt	29	20
Field capacity (%, mass basis @0.05 b)	30.4	26.6
Soil bulk density (t m^{-3})	1.22	1.34

5.2.2 Fertiliser materials

The study of the nutrient release characteristics was conducted by comparing OMF_{15} with mineral fertilisers. These were preferred to organic-based materials as they provided a more reliable source for comparisons with OMF considering that OMF-N and -P are mostly inorganic. Only one type of OMF was used which allowed maintaining the experiment within a manageable size in terms of the chemical analyses needed and there was not a particular reason to choose either OMF_{15} or OMF_{10}. Initially, since the primary focus of the work was on nitrogen, a more concentrated product with a smaller C:N ratio was preferred. OMF_{15}-treated soils were compared against urea (46:0:0) and single super-phosphate (0:18:0) respectively for the study of nitrogen and phosphorus availability following application of the fertiliser to the soil. In both studies, a control soil with no fertiliser added was also used. The experiment used two nitrogen and phosphorus application rates which were equivalent to 150 and 300 kg [N] ha^{-1}, and 150 and 300 kg [P_2O_5] ha^{-1} respectively. The actual quantities of fertiliser applied to individual pots are shown in **Tables 5.2a-b.**

Table 5.2a: Amounts of fertiliser added to incubation pots for the study of nitrogen availability from OMF_{15}.

	Fertiliser material (mg of product per pot)					
Equivalent rate (kg [N] ha^{-1})	**Clay loam**			**Sandy loam**		
	OMF_{15}	**OMF_{15}**	**Urea**	**OMF_{15}**	**OMF_{15}**	**Urea**
	Pilot study	**1st & 2nd runs**	**-**	**Pilot study**	**1st & 2nd runs**	**-**
0	0	0	0	0	0	0
150	125.1	76.6	26.7	113.9	69.7	24.3
300	250.2	153.2	53.5	227.8	139.5	48.7

Table 5.2b: Amounts of fertiliser added to incubation pots for the study of phosphorus availability from OMF_{15} [SSP: single super-phosphate (0:18:0)].

Equivalent rate (kg $[P_2O_5]$ ha^{-1})	Fertiliser material (mg of product per pot)			
	Clay loam		Sandy loam	
	OMF_{15}	SSP	OMF_{15}	SSP
0	0	0	0	0
150	339.6	68.3	309.2	62.2
300	679.3	136.6	618.5	124.4

Four replicates per treatment were needed to facilitate the statistical analysis and take account of some expected variability in the chemical analyses (Kokkora, 2008). The composition of OMF_{15} was previously reported in **Chapter 3** and it corresponded to the material supplied in 2007 for the pilot investigation on nitrogen, and the material supplied in 2008 for the first and second sets of trials for nitrogen and the study of phosphorus respectively. The differences in the amounts of OMF_{15} applied in 2007 and 2008 were due to differences in the concentration of total nitrogen in the two fertiliser batches as reported earlier in **Chapter 3**. In addition, the differences in the amounts of fertiliser applied on the two soil types were due to differences in the soil bulk density values which were presented in **Table 5.1**.

5.2.3 Soil incubation

Incubation pots of 0.25 litres capacity were filled with 200 g of air-dried soil previously ground to pass a 2 mm sieve, mixed with fertiliser and wetted-up with de-ionised water to reach field capacity. Subsequently the pots were placed in an incubator in the absence of light and the temperature in the chamber adjusted to be constant at 25°C (Smith et al., 1998; Leytem, et al., 2004). Moisture content was regularly replenished by adding de-ionised water to the incubation pots on a mass basis which is a common technique in this type of studies (Smith et al., 1998; Smernik et al., 2004). As highlighted earlier, the soil was maintained between field capacity and 75% of field capacity throughout the experiment. This method has been satisfactorily used in previous studies (e.g. Flavel and Murphy, 2006) although earlier studies (Serna and Pomares, 1992) adjusted soil moisture content to a lower level (e.g. ⅔ of field capacity). Soil incubation studies conducted by Leytem et al. (2004) to determine P-solubility and P-bioavailability from a number of organic-P sources used 80% of field capacity. The duration of the study was 120 days for the pilot experiment on nitrogen in 2007 and 90 days for the other two set of trials conducted in 2009 for the study of nitrogen and phosphorus respectively.

This was in line with the guidance provided by OECD (2002) which suggests that a decline in the microbial activity may be observed under such experimental conditions when the incubation period is in excess of 120 days long. The incubation chamber and pots are shown in **Figure 5.1.**

Figure 5.1: A picture showing the incubation experiment; chamber (left), and close-up of incubation pots (right). A plastic tray filled with water was placed inside the chamber to minimise losses by evaporation and maintain the humidity of the air within the chamber (Kokkora, 2008).

5.2.4 Measurements and analyses

Soil sampling was conducted before the fertiliser application; i.e. start of the experiment, and every 30 days thereafter. The sampling was non-destructive as the same pot and soil were used throughout the experiment. For the sampling, the pot was emptied on a plastic tray and the soil thoroughly mixed before the sample (20 g of soil) was taken. The remaining soil was placed back into the pot, weighted and re-wetted to reach field capacity before being returned into the incubation chamber. For the study of nitrogen, the soil was analysed for determination of total nitrogen (Dumas, 1831) prior to the fertiliser application and at the end of the incubation period, and soil mineral nitrogen (MAFF, 1986; Method No.: 53) prior to the fertiliser application and every 30 days thereafter. For the study of phosphorus only soil extractable phosphorus (Olsen et al., 1954; BS 7755 Section 3.6, 1995) was determined. The percentage nitrogen available was calculated in relation to the total nitrogen applied at 30, 60 and 90 days (**Equation [5.1]**) following the procedure employed by Kokkora (2008) who was based on the work of Chaves et al. (2004). The same procedure was applied for the estimation of phosphorus availability (**Equation [5.2]**).

$$\%N_{available} = \frac{Mineral\ N\ fertilised\ soil - Mineral\ N\ control\ soil}{Total\ N\ applied} \times 100$$ **[5.1]**

Where:

$\%N_{available}$: net nitrogen available in the soil determined at 30, 60, and 90 days following fertiliser application to the soil.

Soil mineral nitrogen includes both $NH_4^+ - N$ and $NO_3^- - N$ (Batey, 1988); therefore, both nitrogen fractions were computed for the calculation of the total mineral nitrogen at any given time.

$$\%P_{available} = \frac{Extractable\ P\ fertilised\ soil - Extractable\ P\ control\ soil}{Total\ P\ applied} \times 100$$ **[5.2]**

Where:

$\%P_{available}$: net soil extractable-P determined at 30, 60, and 90 days following fertiliser application to the soil.

Summary of experimental design: the experiments comprised the use of two soil types (sandy loam and clay loam), two fertiliser types (OMF_{15} and urea or SSP), two fertiliser application rates (150 and 300 kg [N] or [P_2O_5] ha^{-1}) and the controls (zero-fertiliser). All treatments (including controls) were replicated four times which resulted in 40 incubation pots for each set of experiments (32 treated-pots and 8 unfertilised controls).

5.2.5 Statistical analysis

Statistical analyses (**Appendix A.5.1**) were undertaken using GenStat Release 10.1 (2007) and applying repeated measurement of analysis of variance. The analyses were graphically verified by means of the residual plots and normalisation of the data was not required.

5.3 Results and discussion

5.3.1 Initial soil analyses

In general, the amounts of ammonium-N encountered were negligible compared with nitrate-N; hence, soil mineral nitrogen could be considered to be equivalent to nitrate-N in most cases.

This was also an indication that the conversion of ammonium into nitrate occurs rapidly (Black, 1968; Darwich, 1998). The results are presented in the form of soil mineral nitrogen (SMN) in relation to the time for each sampling event. Smith et al. (1998) suggested the accumulated thermal time (d°C; base temperature =0°C) can provide a possible link between data obtained in laboratory conditions and the patterns of mineral-N formation observed in-field conditions (Honeycutt et al., 1991). **Table 5.3** shows the results of the soil chemical analyses conducted prior to the start of the experiment which corresponds to the baseline levels for all incubation studies.

Table 5.3: Soil analyses conducted prior to the start of the experiments in the laboratory (n=3; *SD*: standard deviation).

Determination	Sandy loam	*SD*	Clay loam	*SD*	Method
Soil pH	6.91$^{(*)}$	0.24	6.22$^{(*)}$	0.19	MAFF (1986) Method No.: 32
SOM (%, w w^{-1})	3.84	<0.01	5.85	0.02	MAFF (1986) Method No.: 56
C:N ratio	11.4	0.35	10.6	0.17	-
SMN (mg kg^{-1})	14.6	0.14	31.1	0.58	MAFF (1986) Method No.: 53
Extractable P (mg kg^{-1})	72.4	1.18	79.9	0.98	Olsen et al. (1954); BS 7755 S 3.6 (1995)
Extractable P (mg l^{-1})	96.9	1.59	97.5	1.20	-
P-index	5	-	5	-	MAFF (2000)
Total C (%, w w^{-1})	1.80	0.14	1.83	0.01	BS 7755 Section 3.8 (1995)
Total N (%, w w^{-1})	0.143	0.01	0.164	<0.01	Dumas (1831); BS EN 13654-2 (2001)
Total P (mg kg^{-1})	1070.1	-	1326.3	-	US EPA Method No.: 3051

$^{(*)}$Value of soil pH is quoted as a reference from the value reported in the Glasshouse studies (**Chapter 6**).

5.3.2 Nitrogen release characteristics

i. Pilot investigation

The statistical analyses indicated that, overall, soil mineral nitrogen (SMN) in the clay loam soil was significantly higher than the sandy loam soil ($p<0.001$) which was attributable to the higher level of soil organic matter as shown above (**Table 5.3**). Significant differences in SMN were also found between the control soils (no fertiliser added) and the treatments ($p<0.001$). In addition, and across the whole experiment, there were significant differences with respect to the fertiliser type ($p=0.007$) and the application rates used ($p<0.001$). Urea-amended soils resulted in larger amounts of SMN compared with both the controls and the soils treated with OMF_{15} (mean values of SMN were equivalent to 142.3, 126.8, and 68.2 mg [N] kg^{-1} for urea, OMF_{15} and controls respectively; $LSD_{[5\% \text{ level}]}$ values of 13.51 and 11.03 for comparison between the treatment and controls, and between the treatments respectively).

When the nitrogen application rate was increased from 150 to 300 kg [N] ha^{-1}, soil mineral nitrogen increased from 100.1 to 168.9 mg [N] kg^{-1} (LSD$_{[5\% \text{ level}]}$ =11.03). The interaction between the fertiliser type and the rate did not produce a significant effect (p-values of 0.997 and 0.781 for the interaction across the whole experiment and for comparisons within the soils respectively). When factoring in the time, significant differences in soil mineral nitrogen were observed in each sampling event ($p<0.001$) and also between the control and the treatments with respect to the time ($p<0.001$). In addition, both the effect of the treatments and the nitrogen application rates showed significant differences in soil mineral nitrogen with respect to the time although the rate was found to have a stronger effect (p-values of 0.022 and <0.001 respectively). The results obtained in this pilot investigation are shown in **Figures 5.2** and **5.3** for the sandy loam and clay loam soils respectively. SMN was found to increase progressively during the first 90 days from the start of the experiment. This was followed by a decline in the level of SMN observed in the fourth sampling event at 120 days after the fertiliser application. A similar pattern was also observed for the control soils where this decrease occurred after 90 days from the start of the incubation. The largest increase in SMN was found to occur during the first 30 days and it can be attributable to the effect of $NH_4^+ - N$ being rapidly released from urea which is present in both fertiliser materials (mean values of SMN at 30 days were 47.6, 112.3 and 164.6 mg [N] kg^{-1} for the control, OMF$_{15}$- and urea-treated pots – the mean initial value of SMN was 22.9 mg [N] kg^{-1}; LSD$_{[5\% \text{ level}]}$ values of 28.3 [max.rep] and 34.6 [max-min.rep] respectively).

OMF$_{15}$-N requires more time to become available compared to urea; SMN in OMF$_{15}$-treated pots reached approximately the same level as urea at approximately 90 days from application the application of the fertilisers (mean values of SMN at 90 days of 211.5 and 196.5 mg [N] kg^{-1} for OMF$_{15}$ and urea respectively; LSD$_{[5\% \text{ level}]}$ =28.28). The decrease in the level of SMN recorded in the fourth sampling event (120 days) can be attributable to N-immobilisation and possible gaseous losses as a result of denitrification. Although losses by denitrification may be difficult to justify as anaerobic conditions were avoided, it is possible that this process was enhanced by the excess mineral nitrogen in the system after 90 days. Rowell (1994) suggested that losses of N by denitrification are minimised when the soil is maintained at approximately 60% of field capacity. The fact that the soil was maintained at/in the proximity of field capacity could have provided the opportunity for this process to take place. This was not observed until late in the experiment due to the combination of two processes occurring in parallel; first, until day 90, N mineralisation largely surpassed nitrogen losses and N-immobilisation. As a result, there was an excess of SMN in the system which could have enhanced nitrogen losses.

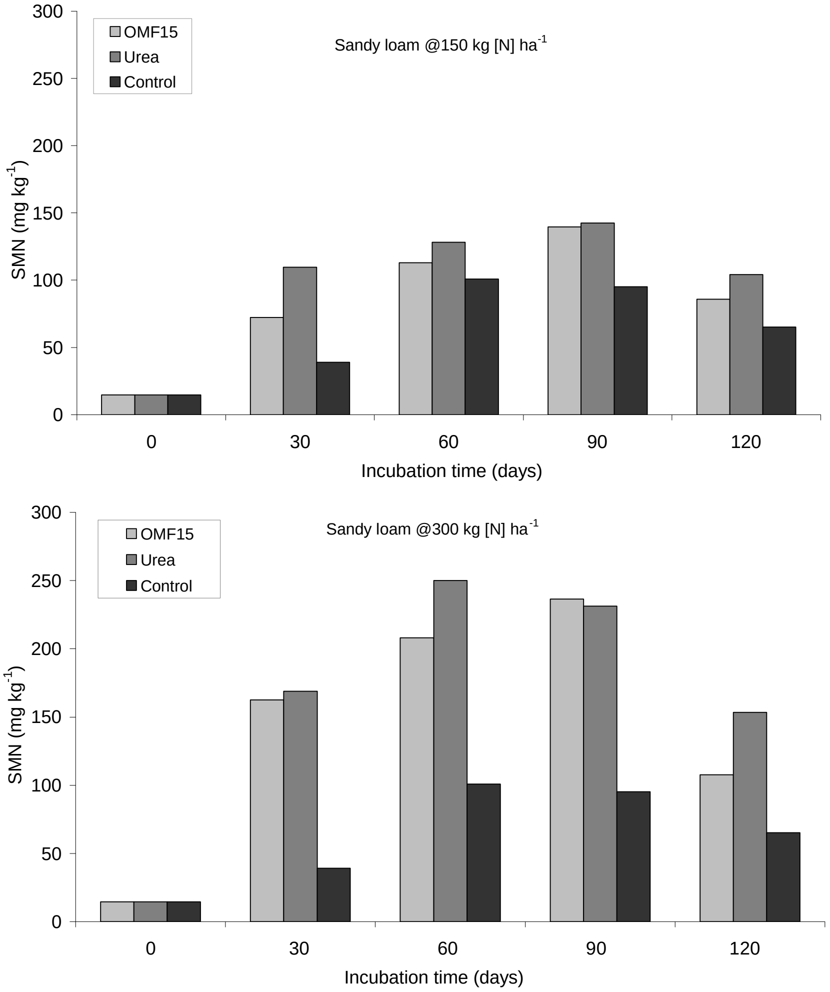


Figure 5.2: Soil mineral nitrogen content following application of urea and OMF$_{15}$ to the sandy loam soil in the pilot investigation; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} (p=0.405; LSD$_{[5\% \text{ level}]}$ =56.57; n=4).

In addition, it is possible that anaerobic zones had occurred in the pot especially immediately after the addition of deionised water. Water would move by gravity and deposit at the bottom of the pot creating a gradient of moisture content from the top to the bottom with un-uniform moisture content, the bottom being wetter than the top, possibly above field capacity. This being responsible for localised anaerobic conditions in the soil which promoted denitrification under the prevailing experimental conditions. There is also evidence (OECD, 2002) which suggested that microbial activity can decline after 90-120 days in such experimental conditions which provides a possible explanation for the relatively low increases in SMN encountered after 60 days from the start.

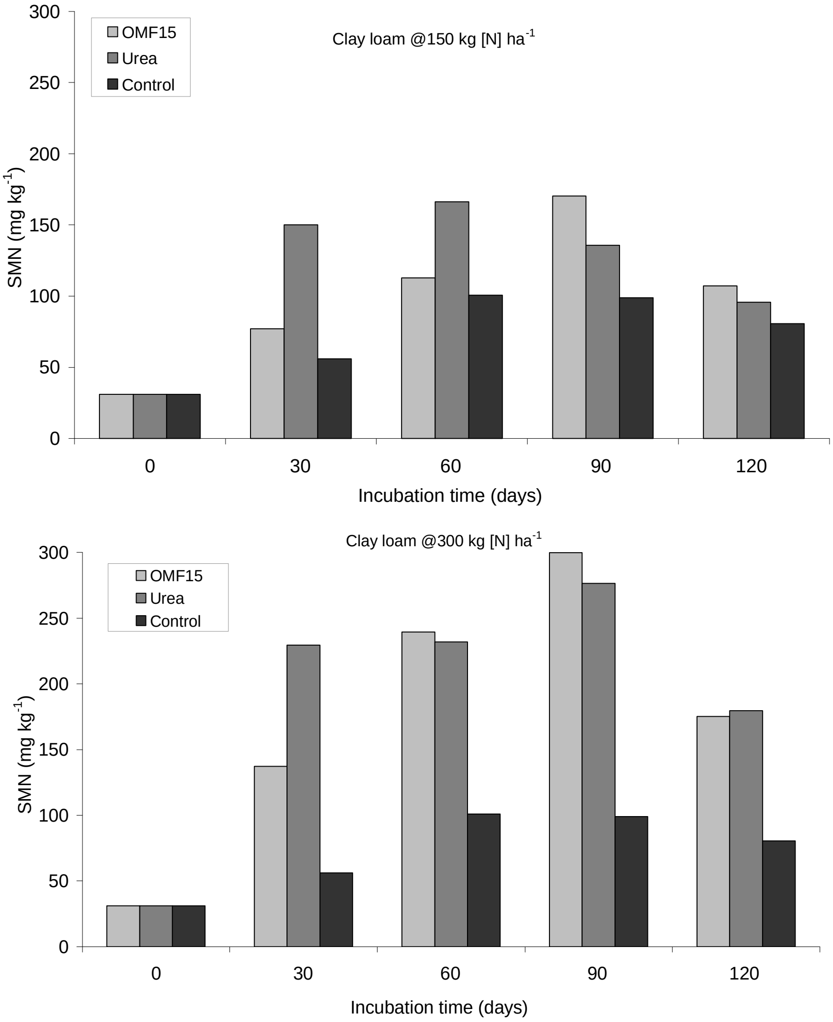


Figure 5.3: Soil mineral nitrogen content following application of urea and OMF$_{15}$ to the clay loam soil in the pilot investigation; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} (p=0.405; LSD$_{[5\% \text{ level}]}$ =56.57; n=4).

The analysis of total soil nitrogen indicated that there were significant differences between the two soil types used (p<0.001) and also compared with the total nitrogen levels at the start of the experiment; i.e. before the application of the fertiliser, and at the end of the 90 days incubation period (p=0.002). Total soil nitrogen increase from 0.143% to 0.153% (sandy loam) and from 0.164% to 0.172% (clay loam) for a LSD$_{[5\% \text{ level}]}$ value of 0.0063. In addition, the effects of the fertiliser type or the nitrogen application rate on the increase of total soil nitrogen were not significant (p-values of 0.204 and 0.136 respectively) and the same nonsignificant effect was encountered for the interaction between the two factors (p=1.00). Overall, across the whole experiment, significant differences were found between the control and the treatments (p=0.031).

Mean values of total nitrogen for the controls and the treatments were 0.152% and 0.159% ($LSD_{[5\% \text{ level}]}$ =0.0059). Therefore, it is possible to state that the addition of fertiliser to the soil induced significant changes in the total soil nitrogen stock.

ii. Nitrogen – first and second runs

As reported for the pilot experiment, in the **first run**, the clay loam soil resulted overall in significantly larger amount of SMN throughout the experiment compared with the sandy loam soil ($p<0.001$). This was also attributable to the higher level of soil organic matter in the clay loam soil as the soils were collected from the same site at the College Farm at Silsoe. Similarly, significant differences in SMN were found between the control and the treatments ($p<0.001$), and with respect to the fertiliser type ($p<0.001$) and the nitrogen application rates used ($p<0.001$). A distinctive feature compared to the pilot investigation was that the interaction between the treatments and the rates was found to be significant ($p<0.001$).

Urea amended soils resulted in larger amounts of SMN compared with the soils treated with OMF_{15} and also the controls (mean values of SMN across the whole experiment equivalent to 123.9, 106.9, and 80.7 mg [N] kg^{-1} for urea, OMF_{15} and controls respectively; $LSD_{[5\% \text{ level}]}$ values of 7.89 and 6.44 for comparisons between the treatments and the controls, and between the treatments respectively). When the nitrogen application rate was increased from 150 to 300 kg [N] ha^{-1}, SMN increased from 99.21 to 131.71 mg [N] ha^{-1} respectively ($LSD_{[5\% \text{ level}]}$ =6.44). The effect of the interaction mentioned above was due to the application of urea at the equivalent rate of 300 kg [N] ha^{-1} which resulted in significantly higher SMN levels than OMF_{15}-N applied at the same rate (mean values for both treatments were 146.8 and 116.7 mg [N] kg^{-1} respectively; $LSD_{[5\% \text{ level}]}$ =9.12).

As for the pilot experiment there were not significant differences between the treatments with respect to the soil ($p=0.679$). However, there was a significant effect of the rate ($p=0.004$) with respect to the soil; i.e. SMN recorded in the clay loam soil fertilised at the equivalent rate of 300 kg [N] ha^{-1} showed, on average, significantly larger amounts of SMN than the same rate in the sandy loam soil (mean values of SMN were 147.8 and 115.6 mg [N] ha^{-1} for an $LSD_{[5\% \text{ level}]}$ value of 8.70). When factoring in the time into the analysis, significant differences in SMN were observed in each sampling event ($p<0.001$) and also between the control and the treatments with respect to the time ($p<0.001$). In addition, both the fertiliser treatments and the nitrogen application rates showed significant differences in soil mineral nitrogen with respect to the time (p-values <0.001).

The results obtained in this experiment are shown in **Figures 5.4** and **5.5** for the sandy loam and clay loam soils respectively. The increase in SMN levels followed a similar pattern to that reported earlier for the pilot investigation with the largest increase occurring within the first 30 days from the start of the experiment. From that point in time SMN remained at approximately the same level throughout the experiment which was observed in both treatments and the controls. In general, SMN remained at a higher level in urea amended soils compared with OMF_{15}. As highlighted in **Section 5.3.1**, it responded to the higher concentration of mineral nitrogen in urea compared with OMF_{15} indicating that this fraction is released almost entirely within 30 days of the application.

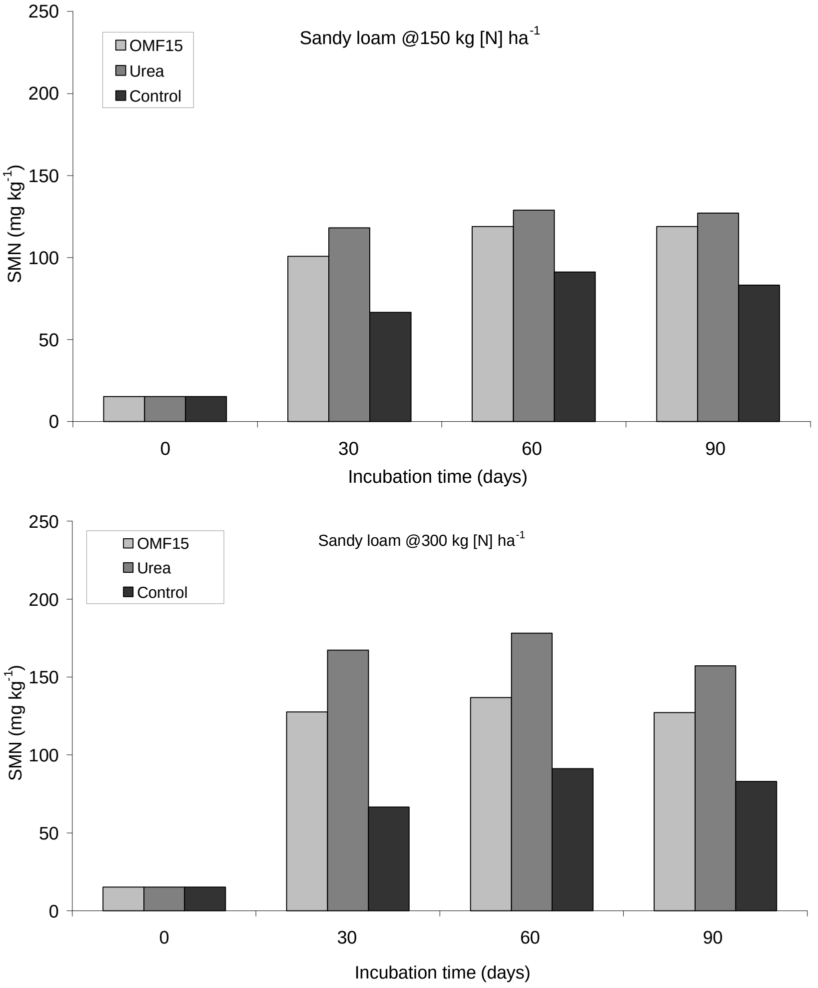


Figure 5.4: Soil mineral nitrogen content following application of urea and OMF_{15} to the sandy loam soil in the first run of the experiment; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} ($p=0.405$; $LSD_{[5\% \text{ level}]}=17.38$; $n=4$).

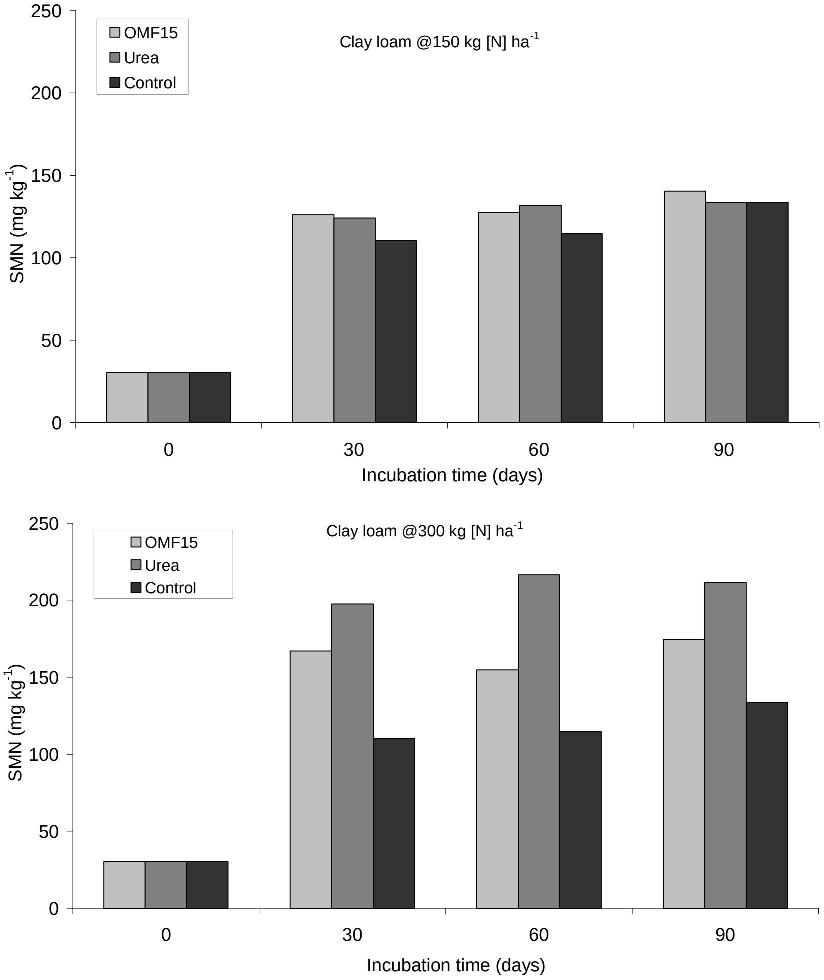


Figure 5.5: Soil mineral nitrogen content following application of urea and OMF_{15} to the clay loam soil in the first run of the experiment; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} (p=0.405; $LSD_{[5\% \text{ level}]}$ =17.38; n=4).

The mineralisation of the organic-N fraction in the OMF_{15} did not appear to have had a significant effect on the total amount of SMN in OMF_{15}-amended soils as it remained consistently lower than that of urea. This suggested that the organic-N fraction is very stable and that it needed more time to become available. As highlighted for the pilot experiment, significant differences in total nitrogen were found between the two soil types used and also between the total nitrogen levels at the start of the experiment; i.e. before the application of the fertiliser, and at the end of the 90 days incubation period (p-values <0.001). There were not significant effects of the fertiliser type or the nitrogen application rate (p-values of 0.073) as well as the interaction between the two factors (p=1.00).

Since no significant differences were found between the control and the treatments (p=0.106) it can be stated that the addition of fertiliser to the soil did not induce significant changes in the total soil nitrogen stock under the prevailing experimental conditions. It also suggests that for the same soil type, losses of nitrogen by denitrification occurred in all treatments, including the controls, at similar rates.

The results of the **second run** of the incubation studies for nitrogen are shown in **Figures 5.6** and **5.7** for the sandy loam and the clay loam soils respectively.

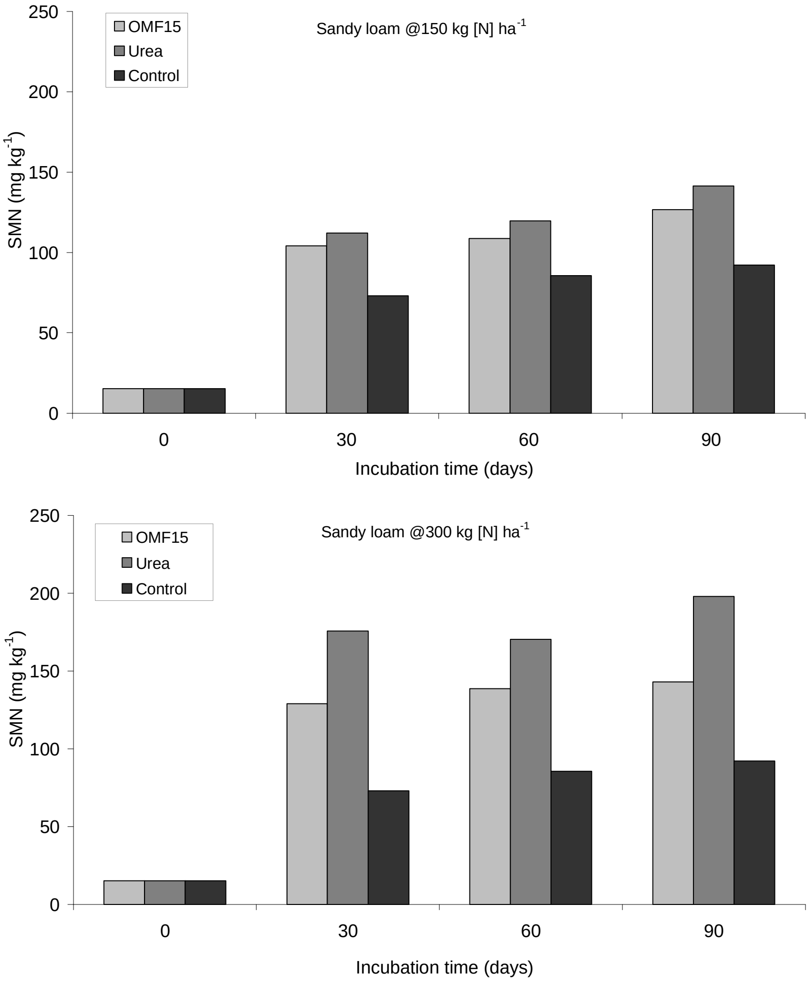


Figure 5.6: Soil mineral nitrogen content following application of urea and OMF_{15} to the sandy loam soil in the second run of the experiment; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} (p=0.769; $LSD_{[5\% \text{ level}]}$ =24.97; n=4).

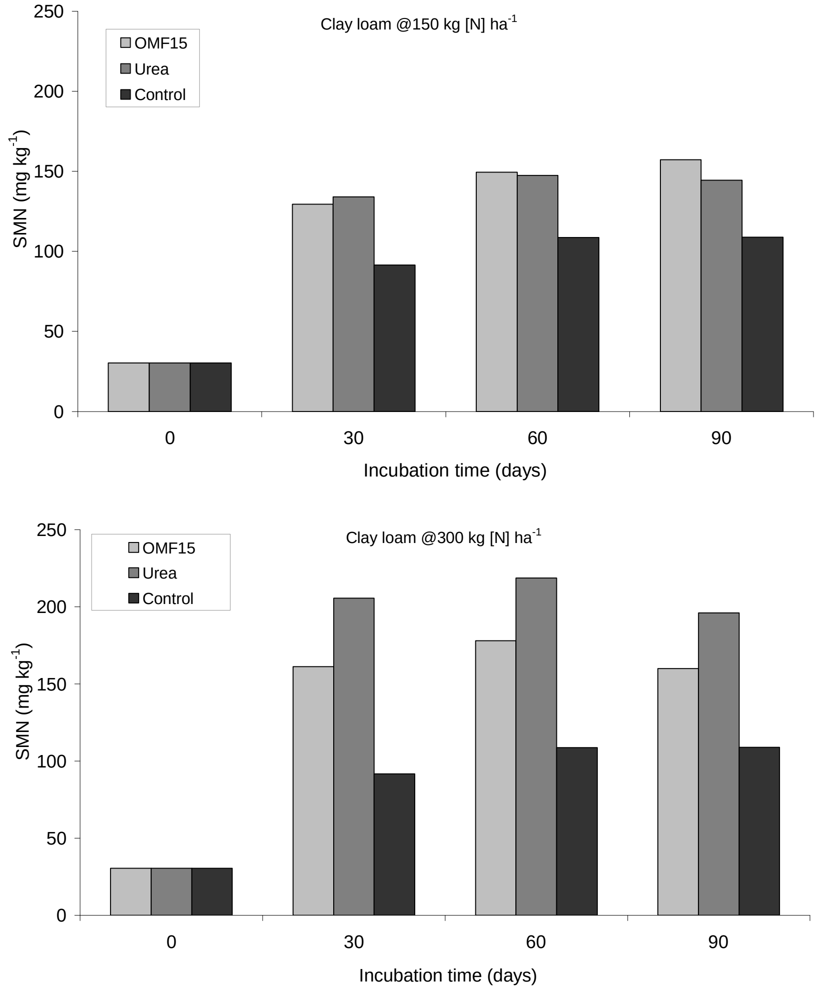


Figure 5.7: Soil mineral nitrogen content following application of urea and OMF_{15} to the clay loam soil in the second run of the experiment; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} (p=0.769; $LSD_{[5\% \text{ level}]}$ =24.97; n=4).

In general, the results of the second incubation experiment on nitrogen showed a similar pattern to that of the previous two studies reported earlier. Overall, urea amended soils produced significantly larger amounts of SMN compared with OMF_{15} and the controls (p-values <0.001). There was however a small increase in the amount of SMN in the clay loam soil fertilised with OMF_{15} at 150 kg [N] ha^{-1} with respect to urea which was observed at 90 days after the start of the experiment. This increase did not result in a significant differences between the two treatments (p=0.769); therefore, there was not sufficient evidence to support that mineralisation of the organic-N fraction of the OMF_{15} occurred at a significant rate at this point in time (mean values of SMN at 90 days were 144.4 and 157.2 mg [N] kg^{-1} for urea and OMF_{15} amended soils respectively; $LSD_{[5\% \text{ level}]}$ =24.97). There were also significant effect of the rate and the interaction between the rate and the fertiliser type (p-values <0.001).

iii. Discussion – nitrogen release characteristics of OMF_{15}

This section shows the combined results for the three sets of incubation experiments conducted for the study of the nitrogen release characteristics of OMF_{15}. The mean values of SMN obtained for each of the sampling events for urea and OMF_{15} amended soils and the controls with no fertiliser added are shown in **Figures 5.8** and **5.9**. Studies on N mineralisation (e.g. Chae and Tabatabai, 1986; Chescheir et al., 1986; Honeycutt et al., 1991; Smith et al., 1998) indicated that soil type has a significant effect upon the N mineralisation pattern in soils fertilised with organic manures and biosolids. Other research (e.g. Terry et al., 1979; Lindemann and Cárdenas, 1984; Smith et al., 1998) suggested that soil type and properties have, overall, a small effect on nitrogen transformations and in particular on the formation of nitrate-N in soils fertilised with biosolids.

In the current study, when considering the data for the three experiments conducted, the statistical analysis showed that there was not a significant interaction between soil type and incubation time ($p=0.385$). This indicates that the soil type did not have a significant effect on the formation of SMN with respect to the time. Temporary fixation of $NH_4^+ - N$ onto clay particles has been reported to be an important factor controlling the availability of N in some incubation studies (e.g. Tester et al., 1977; Smith et al., 1998). Due to the technique used for the extraction of SMN, the amounts of $NH_4^+ - N$ fixed to clay particles could not be determined in this study. However, the relatively low content of clay in the clay loam soil and the experimental conditions suggest that $NH_4^+ - N$ fixation in the clay loam soil was not significant. The differences observed between the two soil types used in this experiment can be explained by initial differences in the overall fertility status of both soils. Gaseous losses of nitrogen by denitrification and/or ammonia volatilisation have been reported to be responsible for significant errors in estimates of nitrogen availability of organic amendments determined by laboratory incubation (Smith et al., 1998). In this respect, significant losses of N from soils in incubation studies have been ascribed to denitrification (King, 1973; Hsieh et al., 1981). The magnitude of the N losses by denitrification was found to increase with the rate of application of biosolids (Lindemann and Cárdenas, 1984). Terry et al. (1981) indicated that losses of N from incubated soils by means of ammonia volatilisation are usually low when biosolids are thoroughly mixed with the soil which was the case in the present study. In agreement with Terry et al. (1981), and despite the nature of the fertiliser materials used in the experiment (containing urea-N), it is reasonable to state that N losses by volatilisation were negligible given the conditions of the experiment and the soil incorporation of the fertilisers.

A decline in the level of SMN was only observed in the fourth sampling event (120 days after the application of the fertilisers) during the pilot investigation. At this point in time and given the experimental conditions, it is expected that urea had been completely hydrolysed and the $NH_4^+ - N$ converted to $NO_3^- - N$.

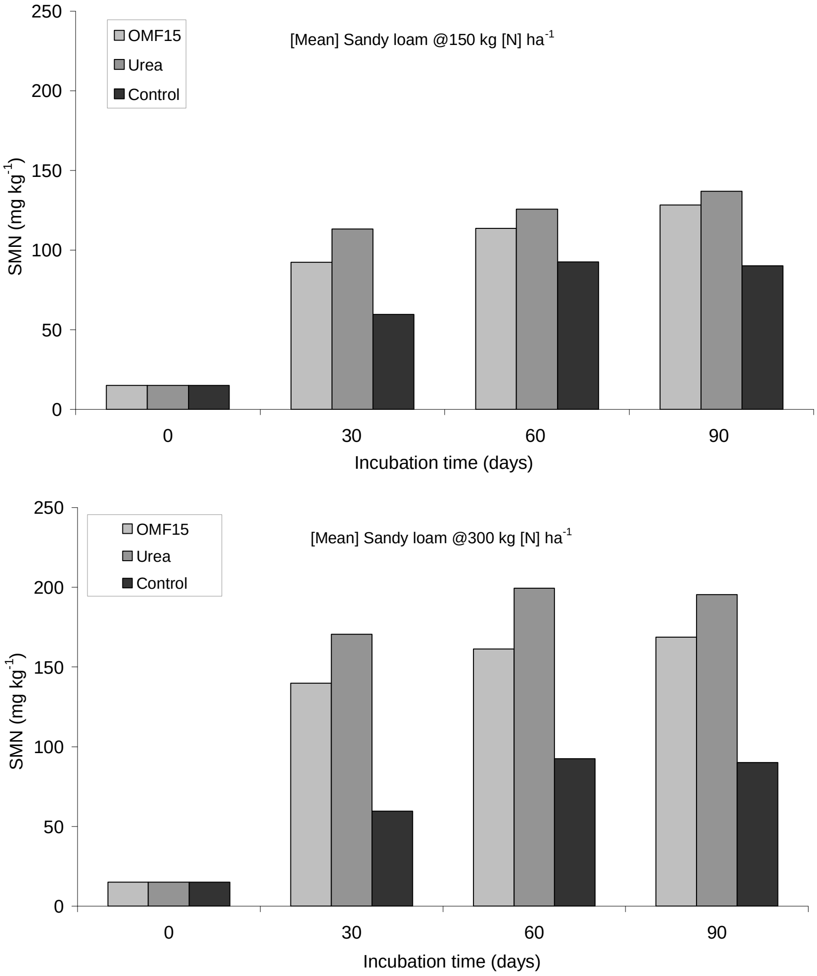


Figure 5.8: Mean soil mineral nitrogen content over 90 days incubation period following application of urea and OMF$_{15}$ to the sandy loam soil; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} (LSD$_{[5\% \text{ level}]}$ =18.23; p=0.431; n=12).

As highlighted earlier, and based on the work of Smith et al. (1998), it possible to correlate the data obtained in laboratory conditions with that from the field. Soil temperatures recorded at the lysimeters station at the College Farm at Silsoe indicated that the accumulated thermal time for the period between 1 March and 30 June, which coincides approximately with the main growth period of winter wheat, was equivalent to 1593 d°C (based on the mean monthly soil temperatures recorded in 2008 and 2009 at a depth of 0.2 m).

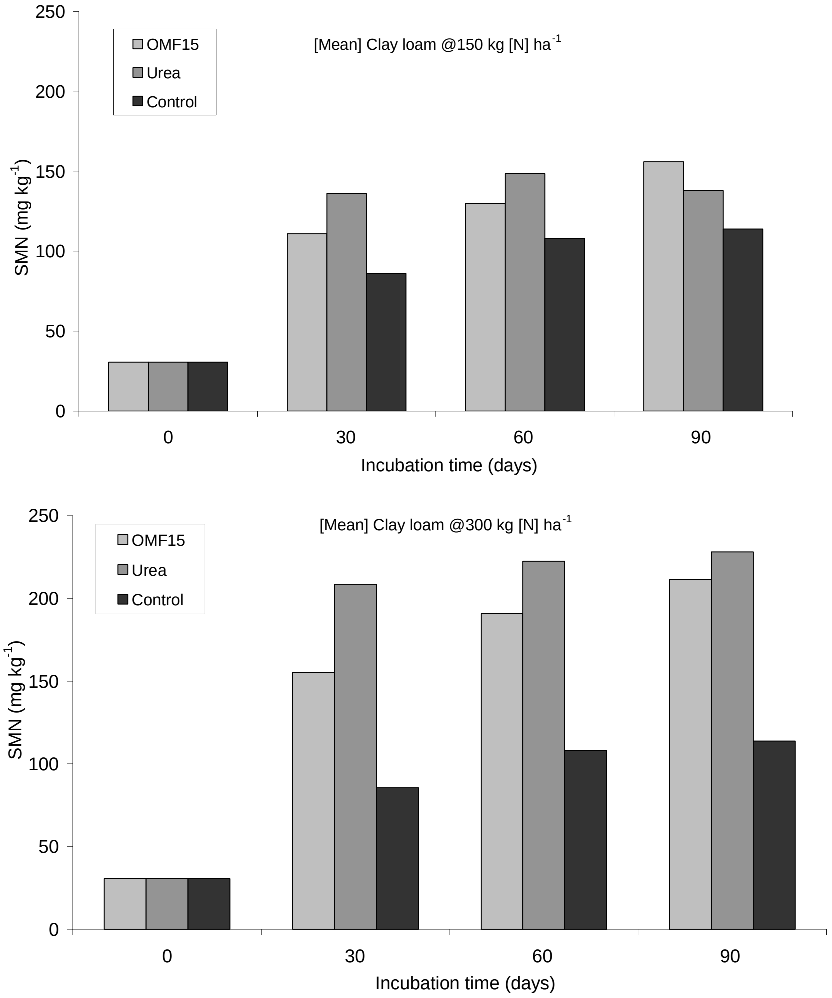


Figure 5.9: Mean soil mineral nitrogen content over 90 days incubation period following application of urea and OMF$_{15}$ to the clay loam soil; (top) 150 kg [N] ha^{-1} and (bottom) 300 kg [N] ha^{-1} (LSD$_{[5\% \text{ level}]}$ =18.23; p=0.431; n=12).

Taking a base temperature equivalent to 0ºC, the incubated soils reached this accumulated thermal time approximately 60 days from the start of the experiment. The net amounts of SMN determined at this stage in the incubated soils (**Figures 5.8** and **5.9**) were equivalent to 47.5 and 201.8 kg [N] ha^{-1} for the clay loam soil fertilised with OMF$_{15}$ at 150 and 300 kg [N] ha^{-1} respectively; i.e. 19.5 and 82.7 mg [N] kg^{-1} respectively. For the sandy loam soil, the OMF$_{15}$ after 60 days from the application yielded 56.3 and 184.2 kg [N] ha^{-1} when applied at 150 and 300 kg [N] ha^{-1} respectively; i.e. 56.3 and 68.8 mg [N] kg^{-1} respectively. This is an indication that OMF$_{15}$ has, overall, some potential to supply relatively high amount of nitrogen to the crop specially when applied at the highest nitrogen rate used in this study.

In both soil types, an accumulated thermal time of 2250 dºC was needed for the OMF_{15} to yield the percentages nitrogen available reported in **Table 5.4a-b** at 90 days. As can be read off the table, the majority of the nitrogen that was released from the OMF_{15} became available within 30 days from the start of the experiment and it was attributed to the rapid release of N from the OMF_{15} fraction carrying urea. At this point (30 days from the start), the accumulated thermal time was 750 dºC. The application of nitrogen to cereal crops is commonly conducted during March and April as highlighted in **Chapter 2**. These two months, based on the same temperatures records indicated earlier, resulted in an accumulated thermal time of 585 dºC.

Unfortunately, it was not possible to produce accurate estimates of nitrogen available from the incubated soils corresponding to this thermal time with the information available (this falls earlier than the first sampling event conducted at 30 days). It is therefore acknowledged that soil sampling at shorter time intervals and also immediately after the start of the experiment would have provided valuable indicators of the nitrogen transformations in the field. The accumulated thermal time of 2250 dºC is likely to be reached in early August in-field conditions suggesting that mineralisation will continue beyond the senescence of the crop which has implications upon nitrogen management.

On one hand, the following crop sown in early autumn; e.g. oil seed rape, will benefit from the residual nitrogen being mineralised in post-harvest of wheat and it may bring about reduced nitrogen requirements for crop establishment (soils with SNS ≤ 2). On the other hand, any unused nitrogen up until harvest is prone to leaching in the autumn especially for late sown crops or possibly second winter wheat crops. Hence, the application of OMF_{15} in early spring may be considered as part of a fertilisation strategy which includes not only the current crop but also the rotation. Based on these results, it may be advisable to apply OMF_{15} early in the spring to maximise the amount of fertiliser-N utilised by the current crop. When the total nitrogen rate is split into two applications, the second dressing may use a mineral nitrogen source whose rate should be adjusted according to the crop requirement and the overall fertility of the soil at the time of the application. This point will be addressed later with the information coming from the studies in the field, as it has been reported (**Chapter 7**) that a first winter wheat crop was benefited from the combined application of mineral nitrogen (first dressing) and OMF (second dressing); i.e. grain yield levels in OMF treated plots were of similar order of magnitude to those that received mineral nitrogen only. The percentages available nitrogen (as % of the total nitrogen applied with the fertiliser) obtained on average from the incubation studies are shown in the following tables for the clay loam and the sandy loam soils respectively (**Table 5.4a-b**).

Table 5.4a: Percentage nitrogen available (as %TN applied with the fertiliser) for OMF_{15} and urea treated soil – Clay loam soil.

	$\%N_{available}$ (%, w w^{-1})			
Soil type	**Clay loam**			
Fertiliser type	**OMF_{15}**		**Urea**	
Time/N-rate	**150 kg [N] ha^{-1}**	**300 kg [N] ha^{-1}**	**150 kg [N] ha^{-1}**	**300 kg [N] ha^{-1}**
30 days	40.45	56.56	81.64	99.94
60 days	35.58	67.26	65.80	92.97
90 days	68.43	79.36	39.29	92.83
Mean	**48.15**	**67.73**	**62.24**	**95.24**
SD	**17.73**	**11.41**	**21.40**	**4.07**

Table 5.4b: Percentage nitrogen available (as %TN applied with the fertiliser) for OMF_{15} and urea treated soil – Sandy loam soil.

	$\%N_{available}$ (%, w w^{-1})			
Soil type	**Sandy loam**			
Fertiliser type	**OMF_{15}**		**Urea**	
Time/N-rate	**150 kg [N] ha^{-1}**	**300 kg [N] ha^{-1}**	**150 kg [N] ha^{-1}**	**300 kg [N] ha^{-1}**
30 days	58.63	71.64	96.12	99.14
60 days	37.43	61.32	59.09	95.41
90 days	68.25	70.31	83.76	94.03
Mean	**54.77**	**67.76**	**79.66**	**96.19**
SD	**15.77**	**5.61**	**18.65**	**2.64**

The sandy loam soil showed relatively high values of soil available nitrogen (as percentage of the total nitrogen applied) which were, on average over the incubation period, comparable to those recorded for the clay loam soil (**Tables 5.4a-b**). This was despite of the larger SOM content in the latter soil, as shown earlier for the analyses conducted prior to the start of the experiment. Cordovil et al. (2005), investigating the mineralisation rates of organic-based fertiliser materials, highlighted that the sandy loam soil used in their incubation studies underwent intense mineralisation and subsequently the rate was reduced after approximately 30 days from the start. Cordovil et al. (2007) highlighted that this pattern of mineralisation had also been reported by the studies of El-Gharous et al. (1990) and Sousa et al. (2002).

To some extent, these observations could provide some grounds to explain the relatively high levels of nitrogen available encountered in the sandy loam soil, based on the assumption that this soil was able to undergo higher mineralisation rates than the clay loam soil under the prevailing experimental conditions and therefore the values of nitrogen available (as percentage of total nitrogen applied) were of similar order of magnitude in both soils. As a reference, the work of Serna and Pomares (1992) reported values of nitrogen available (as percentage of the total nitrogen applied) between 13.8% and 45.6% for soil amended with air-dried sludge at rates of 28 g kg^{-1} [soil] and maintained in incubators at 25°C (N-contents in the sludge in the range of 0.86% to 4.67% by weight and C:N ratios between 5.9 and 13.5). The values reported in the tables above for OMF appeared to relatively higher although the soil fertilised with 150 kg [N] ha^{-1} showed values closer to the upper range reported by Serna and Pomares (1992).

5.3.3 Phosphorus release characteristics

The values of pH encountered in both soil types prior to the start of the experiment (**Table 5.3**) suggested that the availability of P would not be negatively affected by soil pH. The effect of soil pH on soil-P availability has been widely investigated and maximum availability for plant up-take occurs at soil pH ranging between 6 and 7 (Troeh and Thompson, 1993). In general, P retention/fixation is minimal at soil pH in the range of 6.0 to 6.5 (Morgan, 1997). The results of the incubation study for phosphorus are shown in **Figures 5.10** and **5.11** for the sandy loam and the clay loam soils respectively. It is important to highlight that the results of soil extractable-P, as reported by the soil laboratory, need to be converted from [w v^{-1}] to [w w^{-1}]. This conversion was done by multiplying by the soil bulk density (Johnston, 1975).

The statistical analysis revealed that, after an incubation period of 90 days, the application of fertiliser to the soil significantly increased ($p<0.001$) soil extractable-P levels with respect to the control soils where no fertiliser had been added. There were also significant differences in soil extractable-P levels with respect to the soil type ($p<0.001$) which was attributable to the overall higher fertility status of the clay loam compared with the sandy loam soil (mean values were 86.3 and 80.5 mg [P] kg^{-1}, respectively – $LSD_{[5\% \text{ level}]}$ = 0.945). Interestingly, when the values were expressed in mg [P] l^{-1}, the sandy loam soil showed a statistically higher value of soil extractable-P compared with the clay loam soil (mean values of 107.8 and 105.3 mg [P] l^{-1}; respectively – $LSD_{[5\% \text{ level}]}$ =1.25). This was due to the higher soil bulk density encountered in the sandy loam (**Table 5.1**) and despite of the relatively higher soil phosphorus status and SOM encountered initially in the clay loam soil (**Table 5.3**).

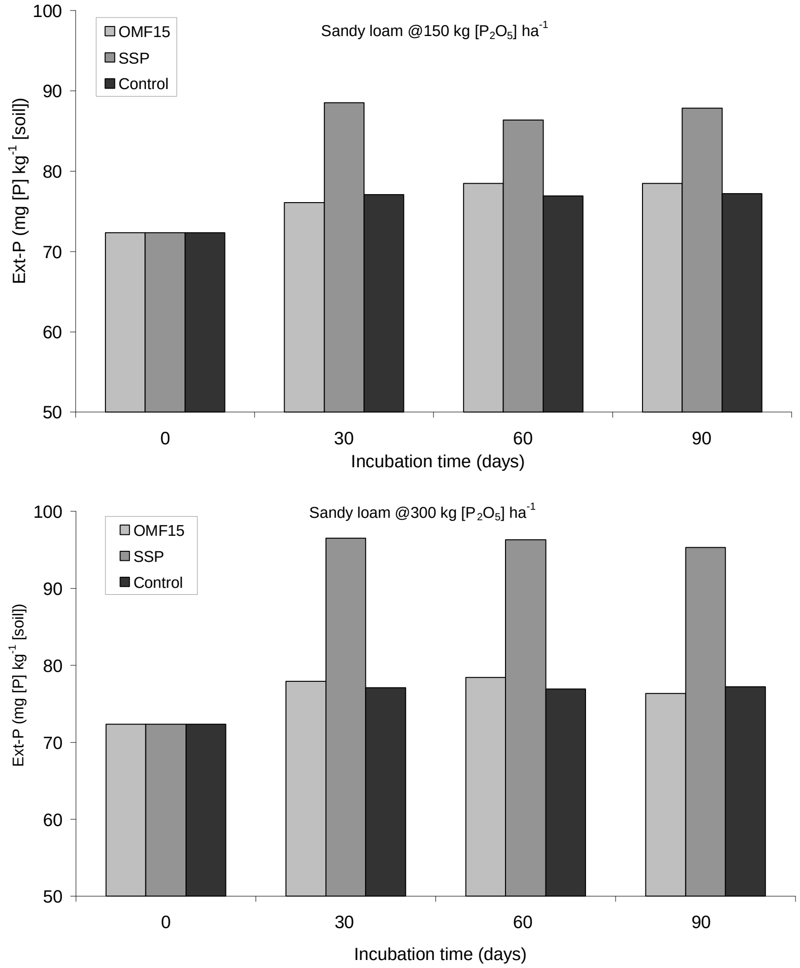


Figure 5.10: Soil extractable phosphorus following application of single superphosphate (SSP) and OMF$_{15}$ to the sandy loam soil; (top) 150 kg [P_2O_5] ha^{-1} and (bottom) 300 kg [P_2O_5] ha^{-1} ($p=0.695$; LSD$_{[5\% \text{ level}]}$ =3.46; n=4).

Significant differences in soil extractable-P were found for the control and the treatment with respect to the fertiliser type ($p<0.001$) and the phosphorus application rate used ($p<0.001$). Although the application of OMF$_{15}$ resulted in soil extractable-P being marginally increased compared with the control, the overall effect of fertiliser application was due to the use of single super-phosphate (SSP). The application of OMF$_{15}$ did not induce a significant increase in soil extractable-P levels compared with the untreated control soil (on average across the whole experiment). Mean values of soil extractable P across the whole experiment were 79.66, 80.01, and 88.62 mg [P] kg^{-1} [soil] for the control, OMF$_{15}$ and SSP amended soils respectively (LSD$_{[5\% \text{ level}]}$ values of 1.29 for comparisons between the treatments and the control, and 1.06 for comparisons between the treatments respectively).

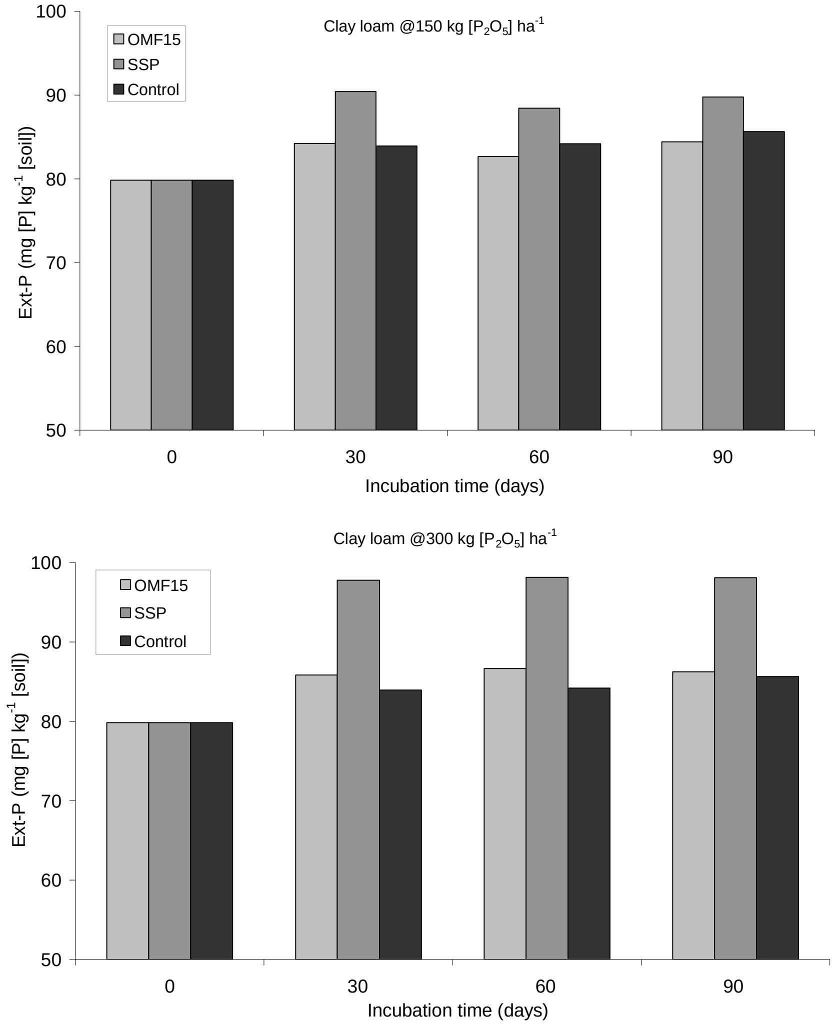


Figure 5.11: Soil extractable phosphorus following application of single superphosphate (SSP) and OMF_{15} to the clay loam soil; (top) 150 kg [P_2O_5] ha^{-1} and (bottom) 300 kg [P_2O_5] ha^{-1} (p=0.695; $LSD_{[5\% \text{ level}]}$ =3.46; n=4).

The values of soil extractable-P encountered in OMF_{15}-treated soil reflected the relatively low solubility of inorganic-P fractions present in the biosolids granules; hence, in the OMF_{15}. These can be associated with the chemical removal of P from the wastewater effluent during the tertiary treatment. At United Utilities plc, the main process for phosphorus removal is by means of precipitation using $FeCl_3$ with the phosphorus being subsequently incorporated into the sludge (Farrant et al., 2008). This process results in the formation of Fe-phosphates which are unavailable for plant up-take. Previous studies (de Haan 1980; Lu and O’Connor 2001) had also highlighted the effect of phosphorus removal by precipitation on the bioavailability of P as insoluble inorganic-P compounds are not readily available for plant up-take.

These phosphorus fractions cannot be detected by routine soil analyses such as Olsen-P (Olsen et al., 1954); hence, the application of OMF_{15}-P to the soil did not induce an immediate change in soil extractable P levels. Chemical analysis performed on the biosolids granules in 2007 (**Chapter 3**) indicated that the amount of water soluble-P was *c*.0.2% P_2O_5 (%, w w^{-1}) which confirms that the majority of the phosphorus in the OMF_{15} is therefore not readily available.

Taylor et al. (1978) highlighted that the net availability of P following application of biosolids to the soil is controlled by chemisorption and precipitation reactions of P and mineralisation of organic-P. Similarly, following application of P fertilisers to the soil, phosphorus is dissolved in the soil water and rapidly immobilised undergoing this kind of reactions with the various soil constituents (Morgan, 1997). Subsequently, the availability of P to crops is governed by the release of P from these reaction products to the soil solution (Morgan, 1997).

This process appeared to have occurred following application of SSP resulting in some immobilisation of P. This is supported by the fact that, despite SSP-P being 92%-94% water soluble-P (MAFF, 2000) not all the P added with SSP was subsequently detected in the soil analyses (**Table 5.4a-b**). The effect being more obvious in the clay loam soil (values of phosphorus available in the soil as percentage of the total-P added in the form of SSP were *c*.15%-25% and 37%-46% for the clay loam and the sandy loam soil respectively). The phosphorus application rates used (**Table 5.2b**) were sufficiently high to allow this process to take place and also to increase significantly the concentration of phosphorus in the soil solution compared with both the control and the OMF_{15} amended soils, as highlighted earlier.

With regards to the phosphorus present in biosolids, EC (2003) stated that a small amount of organic-P in the form of organic phosphates, generally not exceeding 6% (w w^{-1}), may be found in sludges. This organic-P can contain organic-P species in the form of orthophosphate, pyrophosphate and polyphosphate (Hinedi et al. 1989; Cade-Menun and Preston, 1996; Smith et al., 2006). Although the organic-P in the OMF_{15} was not quantified in this particular experiment, to some extent it could have contributed to increase marginally soil extractable-P levels in OMF_{15}-amended soils compared with the unfertilised controls. Johnston and Syers (2006) suggested that when phosphorus is applied to the soil it is rapidly distributed between the various soil-phosphorus pools and as a result, not all the P added with the fertiliser can be subsequently detected by standard soil analyses. According to the authors, the movement of phosphorus between the pools is a reversible process which is mainly driven by plant up-take.

Based on the study of Johnston and Syers (2006), the application of SSP to the soil increases the proportion of P in the soil solution and the readily available pool, both of which are measured by standard soil analyses. In the absence of plant up-take, as it is the case in this experiment, the excess phosphorus in the soil solution and the readily available pool is likely to move to the less readily available and the very slowly available pools. This would occur as a result of the high concentration in the soil solution and the readily available pools respectively following the application of SSP to the soil. There appeared to be an indication of this process taking place as some of the values of soil extractable-P encountered at days 60 and 90 were lower compared with those at day 30 from the start of the experiment. This, however, cannot be fully supported as they are not statistically different ($p=0.695$) and it could be due to differences derived from the analyses. In addition, phosphorus dynamics is relatively slow which makes it difficult to provide a clear understanding of this process in such a short experiment.

Replenishment of phosphorus to the soil solution occurs through mechanisms involving dissolution and desorption reactions which include reaction products from recent phosphorus applied with the fertiliser (mainly soluble P) and also soil phosphorus compounds from previous P-fertiliser applications (Morgan, 1997). Therefore, it is possible that solubilisation of Fe-phosphates can occur in the longer term which would allow to replenish the more readily available pools until the equilibrium between the pools is re-established.

As highlighted earlier, the values of soil extractable-P as expressed in mg [P] l^{-1} were used to determine the soil-P index. Overall, soil-P index was found to increase from 5 (initial level) to 6 in all treatments, and including the control soils, after the 90 days incubation study (**Table 5.5**). For all treatments, except for the sandy loam soil receiving SSP at 300 kg [P_2O_5] ha^{-1}, the change in soil P index was found to occur from the upper limit of index 5 to the lower limit of index 6, as shown in **Table 5.5**. The use of SSP resulted in soil extractable-P being significantly increased ($p<0.001$) after 90 days from the application compared with the controls. The majority of the P released from SSP was available during the first 30 days from the start of the experiment. In-field conditions, this immediate increase in soil extractable-P levels (following application of P-fertilisers) can be counter-balanced by crop up-take in addition to the complex precipitation and adsorption reactions discussed earlier. Therefore, significant changes in the level of soil extractable-P and soil-P index may be difficult to notice in the short term following soil application; particularly, if P is not applied in excess of the crop requirement. From the results of this experiment, it also appears that the availability of P derived from the use of OMF_{15} may be sustained for several years following application.

Wise (1999) stated that on this basis, the use of sludges is better justified to meet crop requirements for P of the whole crop rotation and not for individual years providing soil-P status was already satisfactory. With respect to the residual effect of P-fertilisers, there is evidence (e.g. Kamprath, 1967; Spratt, 1978; Halvorson and Black, 1981-82; Morgan, 1997) which suggests that phosphorus from applied fertiliser can be utilised by crops in subsequent seasons following application (e.g. up 8 to 10 years post-application); that is, in the absence of losses of this applied phosphorus by mechanisms such as run off.

Table 5.5: Changes in soil-P index following application of OMF_{15} and single super-phosphate (SSP) to the soil under controlled laboratory conditions ($p=0.612$; $LSD_{[5\% \text{ level}]}=4.51$; n=4 except initial level n=3). Soil-P indexes 5 & 6 (range 71-100 & 101-140 mg [P] l^{-1}, respectively; MAFF, 2000). T: time in days from the application of the fertiliser. $^{(*)}$Olsen-P (Olsen et al., 1954).

Soil type	**Clay loam**		**Sandy loam**	
Treatment	**P (mg l^{-1})$^{(*)}$**	**P index**	**P (mg l^{-1})$^{(*)}$**	**P index**
Initial level (T=0)	97.45	5	96.90	5
Control (T=90)	104.54	6	103.42	6
OMF_{15} @150 kg [P_2O_5] ha^{-1} (T=90)	103.04	6	105.14	6
SSP @150 kg [P_2O_5] ha^{-1} (T=90)	109.56	6	117.66	6
OMF_{15} @300 kg [P_2O_5] ha^{-1} (T=90)	105.15	6	102.32	6
SSP @300 kg [P_2O_5] ha^{-1} (T=90)	119.70	6	127.76	6

Tables 5.6a-b show the amount of phosphorus available in the soil as percentage of the total phosphorus applied with the fertiliser. The values presented in the tables were calculated by applying **Equation 5.2**; for this, the net value of soil extractable-P expressed in mg [P] kg^{-1} was converted to mg [P_2O_5] kg^{-1} and then divided by the total-P applied with the fertiliser also expressed in mg [P_2O_5] kg^{-1} [soil]. This calculation required the phosphorus application rates shown in **Table 5.2b** (expressed in kg [P_2O_5] ha^{-1}) to be converted to mg [P_2O_5] kg^{-1} [soil] using the soil density values reported earlier in **Section 5.2.1**. For the conversion of P into P_2O_5 a factor of 2.291 was used (MAFF, 2000). The net value of soil extractable-P was obtained by subtracting the value of soil extractable-P corresponding to the control soil to that of the treatment.

Table 5.6a: Phosphorus available in the soil as percentage of the total phosphorus applied with the fertiliser – Clay loam soil [SSP: single super-phosphate].

	---------------------------------- $\%P_2O_5$ (%, w w^{-1}) ----------------------------------			
Soil type	**Clay loam**			
Fertiliser type	**OMF_{15}**		**SSP**	
Time/P-rate	**150 kg [P_2O_5] ha^{-1}**	**300 kg [P_2O_5] ha^{-1}**	**150 kg [P_2O_5] ha^{-1}**	**300 kg [P_2O_5] ha^{-1}**
30 days	1.04	3.50	24.08	25.77
60 days	-5.63	4.55	15.73	25.98
90 days	-4.55	1.06	15.32	23.18

Table 5.6b: Phosphorus available in the soil as percentage of the total phosphorus applied with the fertiliser – Sandy loam soil [SSP: single super-phosphate].

	---------------------------------- $\%P_2O_5$ (%, w w^{-1}) ----------------------------------			
Soil type	**Sandy loam**			
Fertiliser type	**OMF_{15}**		**SSP**	
Time/P-rate	**150 kg [P_2O_5] ha^{-1}**	**300 kg [P_2O_5] ha^{-1}**	**150 kg [P_2O_5] ha^{-1}**	**300 kg [P_2O_5] ha^{-1}**
30 days	-4.13	1.68	46.78	39.76
60 days	6.39	3.07	38.72	39.68
90 days	5.04	-1.82	43.42	37.06

As can be read from the table, the application of OMF_{15}-P to the soil resulted in relatively low percentages of phosphorus available (relative to the total-P applied); this effect was observed in both soil types to approximately the same extent. For SSP-P, the percentage of phosphorus available was found to be higher in the sandy loam soil compared with the clay loam soil which was expected due to the higher SOM and clay contents. O'Connor et al. (2004) indicated that biosolids that had undergone biological phosphorus removal but that had been supplemented with Fe and Al showed low phytoavailability (<25% of the phytoavailability of that encountered with triple superphosphate) which appears to be in agreement with the results shown in the table for OMF_{15}-P.

5.4. Residual OMF and biosolids in post-harvest of wheat

OMF and biosolids granules were collected from the soil surface in post-harvest of wheat to determine their chemical composition (total nitrogen). Sampling was performed by collecting OMF_{15}, OMF_{10} and biosolids particles only from the plots (see **Chapter 7**) that received the highest nitrogen application rates (250 kg [N] ha^{-1}).

Sampling was performed in two occasions, post-harvest of wheat in 2008 in Avenue Field and post-harvest of wheat in 2010 in Chippies Field. The particles collected corresponded to the fertiliser batches produced in 2008 and 2010 respectively. The post-harvest analysis of these particles provided an indication of the extent to which the organic-N fraction had been mineralised in-field conditions during the crop season. The fertiliser applications took place on 3rd April 2008 in Avenue Field and 27th March 2010 in Chippies Field and the particles were collected from the field on the days the harvest took place on 15th September 2008 and 9th August 2010 for Avenue and Chippies Fields respectively.

The composition of the particles is shown in **Table 5.7**. Notice that in all cases the fertiliser was applied on the soil surface and there was not incorporation into the soil following application.

Table 5.7: Chemical composition of OMF_{15}, OMF_{10} and biosolids granules in post-harvest of wheat.

	---------------------------------- TN (%, w w^{-1}) ----------------------------------			
Fertiliser material	**2008[*]**	**Avenue Field[**]**	**2010[*]**	**Chippies Field[**]**
OMF_{15}	16.05	2.62	11.40	2.96
OMF_{10}	10.52	2.60	7.15	2.93
Biosolids	4.53	2.81	5.48	3.70

[*]Original composition.
[**]Composition in post-harvest.

As can be seen from the table, the concentration of nitrogen in the particles collected in post-harvest was reduced to approximately the same level in all materials; these were found to have between 50% and 60% of the total nitrogen content of biosolids granules before their application (original composition) which gives an indication of the extent to which organic nitrogen was broken down over a period of approximately five months.

5.5 Conclusions

The main conclusions coming from **Chapter 5** are summarised below:

- The assessment of the **nitrogen availability** of OMF_{15}, indicated that:
    - The greatest rate of nitrogen release from OMF_{15}, as percentage of the total-N applied, occurred in the first 30 days following soil application. It ranged between 59% (*c*.88 kg [N] ha^{-1}) and 72% (*c*.216 kg [N] ha^{-1}) in the sandy loam, and between 40% (*c*.60 kg [N] ha^{-1}) and 57% (*c*.171 kg [N] ha^{-1}) in the clay loam soil depending on the nitrogen application rate.
    - Subsequently, there was a further 10% increase in the percentage nitrogen available (relative to the total applied) in the sandy loam soil and between 23% and 28% in the clay loam soil.
    - The greatest rate of nitrogen release from urea, as percentage of the total-N applied, also occurred in the first 30 days following soil application. It ranged between 96% (*c*.144 kg [N] ha^{-1}) and 99% (*c*.297 kg [N] ha^{-1}) in the sandy loam and between 82% (*c*.123 kg [N] ha^{-1}) and 99% (*c*.297 kg [N] ha^{-1}) in the clay loam soil depending on the nitrogen application rate. Thereafter, SMN remained relatively constant in most circumstances. Overall, SMN was significantly higher in urea- compared with OMF_{15}-treated soil.
    - An accumulated thermal time of 2250 d°C was needed for OMF_{15} to release between 68% and 70%, and between 68% and 79% of the total-N applied in the sandy loam and the clay loam soils respectively depending on the nitrogen application rate. This accumulated thermal time is likely to be reached in early August in-field conditions which suggested that mineralisation of the organic-N fraction in the OMF would progress after the harvest of winter cereal crops.
- The assessment of the **phosphorus availability** of OMF_{15}, indicated that:
    - Phosphorus availability from OMF_{15}, as percentage of the total-P applied, was low throughout the experiment. It ranged from -4.1% (*c*.6.2 kg [P_2O_5] ha^{-1}) to 6.4% (*c*.9.5 kg [P_2O_5] ha^{-1}) in the sandy loam and from -5.6% (*c*.8.4 kg [P_2O_5] ha^{-1}) to 4.6% (*c*.13.5 kg [P_2O_5] ha^{-1}) in the clay loam soil. The negative values recorded indicated that P-availability was reduced in the treated soils compared with the control. The relatively low availability of OMF-P can be attributable to the technique used for the removal of phosphorus during the wastewater treatment.

- Despite the generally low availability of applied OMF-P, a change in soil-P index from 5 to 6 was observed but the overall increase in soil extractable-P was marginal and it remained close to the initial levels recorded in both soils.
- For single superphosphate (SSP), P-availability (as percentage of the total-P applied) was significantly higher than that of OMF_{15}-P. It ranged from 37% to 46% in the sandy loam, and from 16% to 26% in the clay loam soil. The application of SSP induced a significant increase in soil extractable-P levels compared with the untreated soils. As a result, soil-P index changed from 5 to 6 in both soil types. This was expected given its high solubility (92%-94% water soluble-P).

CHAPTER 6

GLASSHOUSE STUDIES

6 GLASSHOUSE STUDIES

6.1 Introduction

The glasshouse studies were conducted to supplement the research undertaken in the field which is reported in **Chapter 7**. One of the advantages of the studies in the glasshouse was that it provided the opportunity to conduct the investigation in parallel to the field work. It is worth noting that rye grass was not introduced in Avenue Field until the spring of 2009 for which the glasshouse studies facilitated the compliance with the time-scale allocated to the experimental work of the project. The three years' investigation in the glasshouse generated substantial technical data which helped in the assessment of the effects of the application of OMF on both the soil and the productivity of the grass under controlled environmental conditions.

Therefore, the aim of this chapter is to further contribute to the understanding of nutrients management and dynamics related to the use of OMF in crop production and it follows on the data-analysis and discussion presented in the previous chapter. The findings coming from this study will aid the development of a set of practical recommendations for the best use of OMF in grass production. The objectives of the glasshouse studies are summarised below:

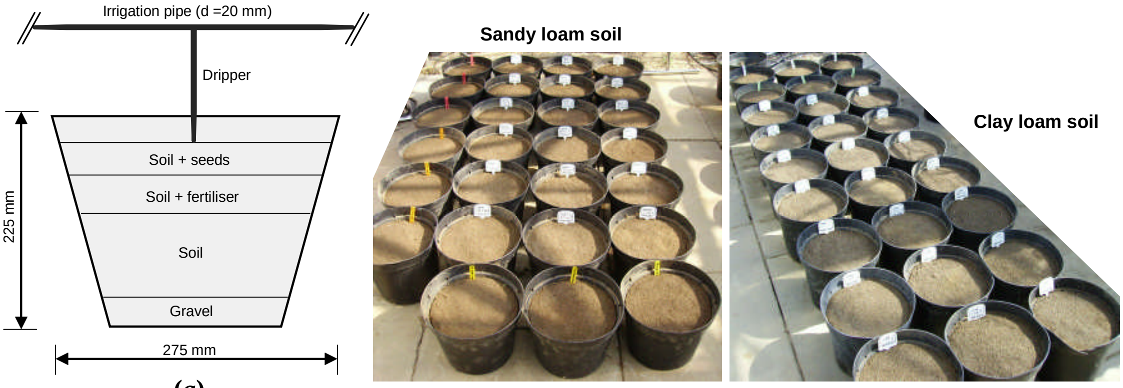
- To investigate dry matter yield and responses of rye grass (*Lolium perenne* L.) to the application of organomineral fertilisers in comparison with urea and biosolids,
- To quantify the nitrogen uptake and the nitrogen use efficiency of rye grass (*Lolium perenne* L.) following the application of the fertiliser types mentioned above, and
- To determine the effects of continuous application of organomineral fertilisers on the fertility status of the soil with particular regards to nitrogen and phosphorus.

6.2 Materials and methods

6.2.1 Details of the experiment

The studies were conducted in a glasshouse and a detailed description of the facility is provided in **Appendix A.6.1.** The experiment used the same soil types as those employed for the incubation studies (**Chapter 5**). These were a sandy loam soil – Cottenham series, and a clay loam soil – Holdenby series (King, 1969; Hodge et al., 1984). The results corresponding to the soil textural analysis, field capacity and soil bulk density were reported earlier in **Chapter 5**.

The soils were also collected from Avenue and Showground Fields respectively at the College Farm at Silsoe. The experiment used pots of 10 litres capacity which were filled with 8 kg of air-dried soil previously ground to pass a 2 mm sieve (Cornforth and Sinclair, 1977). The base of the pot was filled with a layer of 25 mm of gravel to allow free drainage and to prevent soil losses. During the preparation of the pots, the fertiliser (**Table 6.1**) was mixed with the soil to conform a layer of approximately 50 mm beneath the grass seeds which prevented them from being in direct contact with the fertiliser during the germination. The wetting-up of the soil was done by adding tap water repeatedly in small amounts to avoid the occurrence of leaching. In the eventuality of leaching, the leachate was collected and poured back on the pot. Subsequently, rye grass seeds were evenly spread on the soil surface at an equivalent rate of 4 g [seeds] m^{-2} and covered with a thin layer of soil to facilitate the germination (**Figure 6.1**).



(*a*) (*b*) (*c*)

Figure 6.1: (*a*) A diagram showing the preparation of a pot; (*b, c*) overview of pots following their preparation.

Sowing was conducted on 27th April 2007 and germination was recorded approximately one week later. A dripping irrigation system which used tap water and was controlled by a timer was installed after the germination of the grass. The irrigation system delivered water at approximately $0.7\times10^{-3} l\ s^{-1}$ per dripper and the time allowed for irrigation was constantly adjusted to maintain the soil moist to ensure crop growth was not restricted by water availability but also to avoid leaching. The pH of the water used for irrigation was measured once, following the relocation of the pots to Cranfield, and it was found to be 7.03 (*SD* =0.05). An overview of the experiment in the glasshouse is shown in **Figures 6.2** and **6.3**.

(*a*) (*b*)

Figure 6.2 (top): Overview of the pot experiment in the glasshouse.

Figure 6.3 (bottom): (*a*) during the germination of the grass, and (*b*) close-up of pots.

Summary of experimental design: it comprised two soil types (sandy loam and clay loam), four fertiliser materials (biosolids, OMF_{10}, OMF_{15} and urea), and two nitrogen application rates (150 and 300 kg [N] ha^{-1}). A completely randomised design was used; all treatments were replicated three times and there were three control pots (zero-fertiliser) for each of the soil types. This experimental design resulted in 54 pots (48 treated- and 6 control-pots). The fertilisers were hand-applied at a single dressing on an annual basis. Due to the inclusion of a second soil type (clay loam) the number of nitrogen rates used in the glasshouse's experiment had to be reduced to two compared with that of field (**Chapter 7**). This permitted maintaining the experiment within a manageable size. By contrast, the upper level of nitrogen fertilisation was higher than that used in the field but it was considered adequate given the experimental conditions in the glasshouse.

The actual amounts of fertiliser (product) applied year on year to each individual pot are shown in **Table 6.1**. These differed between-years as a result of differences encountered in the concentration of nitrogen in the various fertiliser batches produced (**Chapter 3**).

The amount of fertiliser required per pot was calculated on the basis of the (top) area of the pot which was 0.059 m^2.

Table 6.1: Nitrogen application rates and corresponding amounts of fertiliser applied per pot for the three years' experiment in the glasshouse.

Treatment	Fertiliser product (g pot^{-1})					
Year	**2007**		**2008**		**2009**	
Equivalent rate (kg [N] ha^{-1})	**150**	**300**	**150**	**300**	**150**	**300**
Biosolids	22.90	45.81	19.67	39.34	22.44	44.89
OMF$_{10}$	10.96	21.92	8.47	16.94	9.05	18.09
OMF$_{15}$	9.06	18.13	5.55	11.10	6.38	12.77
Urea	1.94	3.87	1.94	3.87	1.94	3.87

The amounts of P_2O_5 and K_2O applied annually to individual pots with the fertilisers are given in detail in **Appendix A.6.2**. The fertilisers were always applied in a single dressing which made it easier considering the relatively small amounts of fertiliser applied per pot (**Table 6.1**). These were applied on the soil surface and immediately after the first cut of the grass was conducted (except for the year of establishment when the fertilisers were incorporated during the preparation of the pots). In practice, however, the application of nitrogen to grass is divided up to 6 times in the season depending on the total nitrogen load and on the use of the grass sward (MAFF, 2000). A total of three cuts were performed annually throughout the growing season (April-October).

Therefore, the design of the experiment required 54 pots; i.e. 27 pots for each of the two soil types (3 unfertilised control pots and 24 fertiliser-treated pots). The arrangement of the pots in the glasshouse and the treatments are shown in **Appendix A.6.3**. Weeds were controlled manually by removing the plantules from the pots.

6.2.2 Crop and soil measurements and analyses

The two soil types used in the glasshouse studies were sampled prior to the start of the experiment in March 2007 following their collection from the field. The results of chemical analyses conducted are shown in **Table 6.2.** The results of this first set of analyses represent the baseline level in the soil.

Table 6.2: Soil analyses conducted prior to the start of the experiments in the glasshouse (*SD*: standard deviation; n=3).

Determination	Sandy loam	*SD*	Clay loam	*SD*	Method
Soil pH	6.91	0.24	6.22	0.19	MAFF (1986) Method No.: 32
SOM (%, w w^{-1})	3.68	0.03	5.10	0.02	MAFF (1986) Method No.: 56
C:N ratio	10.95	0.02	11.96	0.02	-
SMN (mg kg^{-1})	13.1	0.02	23.7	0.20	MAFF (1986) Method No.: 53
Extractable P (mg kg^{-1})	73.02	0.02	82.29	0.02	Olsen et al. (1954); BS 7755 Section 3.6 (1995)
Extractable P (mg l^{-1})	97.85	0.03	100.40	0.02	-
P-index	5	-	5	-	MAFF (2000)
Extractable K (mg kg^{-1})	211.7(*)	1.44	334.1	2.27	MAFF (1986) Method No.: 63
Extractable K (mg l^{-1})	283.7(*)	1.93	407.5	2.77	-
K-index	3	-	4	-	MAFF (2000)
Extractable Mg (mg l^{-1})	86.31	-	97.22	-	MAFF (1986) Method No.: 40
Mg-index	2	-	2	-	MAFF (2000)
Total C (%, w w^{-1})	1.59	0.07	2.30	0.12	BS 7755 Section 3.8 (1995)
Total N (%, w w^{-1})	0.145	<0.01	0.192	<0.01	Dumas (1831); BS EN 13654-2 (2001)

(*)Value of extractable-K is quoted as a reference from the value reported for Avenue Field **(Chapter 7)**

In addition to the soil analyses listed in **Table 6.2**, a number of determinations were routinely performed both in the crop and the soil while the experiment was conducted (**Table 6.3**).

Table 6.3: Details of soil, crop and water analyses conducted during the experiment in the glasshouse. Methods of analysis are identical to those shown in Table 7.2.

Determination	Timing of sampling and analysis
TN$_{soil}$	▪ Annually, before fertiliser application (2007-2009) ▪ End of experiment, 2009
SMN	▪ Annually, before fertiliser application (2007-2009) ▪ End of experiment, 2009
Extractable P	▪ End of experiment, 2009
Soil pH	▪ End of experiment, 2009
SOM	▪ End of experiment, 2009
Total above-the-ground biomass	▪ Annually, 3 times between April and October (2007-2009)
TN$_{plant}$	▪ Harvested plant material, 2007 and 2008
TP$_{plant}$	▪ 1st harvest of grass, 2007
pH of water (irrigation)	▪ March 2008 – Cranfield University’s glasshouse

Soil sampling was always conducted to the full available depth of soil in the pot (200 mm) by extracting three sub-samples with a small auger (15 mm in diameter) and subsequently re-filling the holes with the same soil type (stored from the same batch of soil collected in March 2007). Sampling on the inner edges of the pots was avoided as there was some deposition of salt from the evaporation of irrigation water. The grass was cut at 20 mm above the soil surface (Cordovil et al., 2007) and the harvested plant material was subsequently oven-dried at 60°C for 48 hours (MAFF, 1986; Method No.: 1) for determination of total above-the-ground biomass. This is reported as dry matter yield expressed in kg [DM] ha^{-1}. In a similar study, Kokkora (2008) performed four cuts per year but in the present work, there was a need to reduce the number of analyses considering also the length of the experiment (three years). The determination of nitrogen in plant material (TN_{plant}) permitted the estimation of the nitrogen uptake (TN_{uptake}) and the nitrogen use efficiency (NUE) and their results are presented and discussed. NUE was estimated using the difference method which is described in Johnston and Poulton (2009). NUE was estimated by means of the agronomic efficiency (A_E) and the apparent recovery (R_N) of applied nitrogen.

6.2.3 Statistical analyses

Statistical analyses were undertaken to determine the effects of the treatments on the yield of the grass and the measured soil parameters. These included analysis of variance (ANOVA) and the least significant differences to compare the means ($LSD_{[5\% \text{ level}]}$). Repeated measurement of analysis of variance was used to compare the annual yield data as well as that of individual cuts both within- and between-years. The same technique was applied for the statistical analysis of the data corresponding to the measured soil properties (**Table 6.3**). Estimates of the statistical analyses were graphically assessed by means of the residual error plots and the data received the same treatment as that indicated for the studies conducted in the field (**Section 7.2.4**).

Crop (grass) responses to fertiliser application were investigated using generalised linear models. A square term (nitrogen rate square) was included in the model to determine whether the relationships between the nitrogen application rate and the yield were non-linear and the results are discussed. The regression analyses for grass were only undertaken for the annual yield data which was the primary focus of this work. The statistical analyses were conducted using GenStat Release 10.1 (2007) and the results, including the regression analyses, are presented in **Appendix A.6.4**.

6.3 Results and discussion

The following sections report on the results of the studies conducted in the glasshouse. The responses of rye-grass to the application of fertiliser and the effect of the fertiliser treatments on the nitrogen content of the grass are presented in **Sections 6.3.1** and **6.3.2** respectively. In addition, the effects of the fertiliser treatments on the soils and the results of the analyses of the selected soil parameters are presented in **Section 6.3.3**. An overall discussion is presented in **Section 6.4** which leads to the conclusions of this chapter given in **Section 6.5**. The discussion focuses upon the effects of the continuous application of biosolids, OMF and urea on the growth of rye grass and the changes observed in the fertility status of the soil. It uses some elements reported for the field studies (**Chapter 7**) which were of help to support some of the findings encountered but acknowledging the different experimental scales used. A photographic record of the treatments in the first year of the experiment is shown in **Appendix A.6.5**.

6.3.1 Dry matter yield of rye grass

The rye grass established in the spring of 2007 was maintained in production until the 3rd cut was performed in October 2009. The data reported in this section correspond to the annual dry matter yield which is shown in **Figures 6.4**, **6.6** and **6.8** for 2007 to 2009 respectively. **Figures 6.5**, **6.7** and **6.9** show the mean dry matter yield for both the unfertilised control pots and the treatments for 2007 to 2009 respectively. The results of the regression analyses which investigated the relationship between dry matter yield and nitrogen application rate are summarised in **Tables 6.4** to **6.6** for 2007 to 2009 respectively. The yield data corresponding to individual cuts for each of the three years' trial are presented in **Appendix A.6.6**. Comparisons of dry matter yield between years were conducted for all three years but it is worth highlighting that in 2007 the fertilisers were incorporated during the preparation of the pots whereas in the following two years they were surface-applied. Also, in 2007 all fertilisers, with the exception of urea, were ground (**Chapter 3**) prior to the soil incorporation which changed their physical characteristics. Another important feature is with regards to the number of days allowed before a cut was conducted. Although the dates of the cuts did not match exactly between the years they were all conducted within ±15 days from each other. Hence, the timing of fertiliser application following the first cut in 2008 and 2009 also differed slightly (±2 days). The number of days recorded between the first and the third cuts each year was 80, 100, and 105 days for 2007, 2008 and 2009 respectively. These are important aspects related to the management of the grass which needed to be acknowledged to help interpreting some of the differences observed in the experimental data.

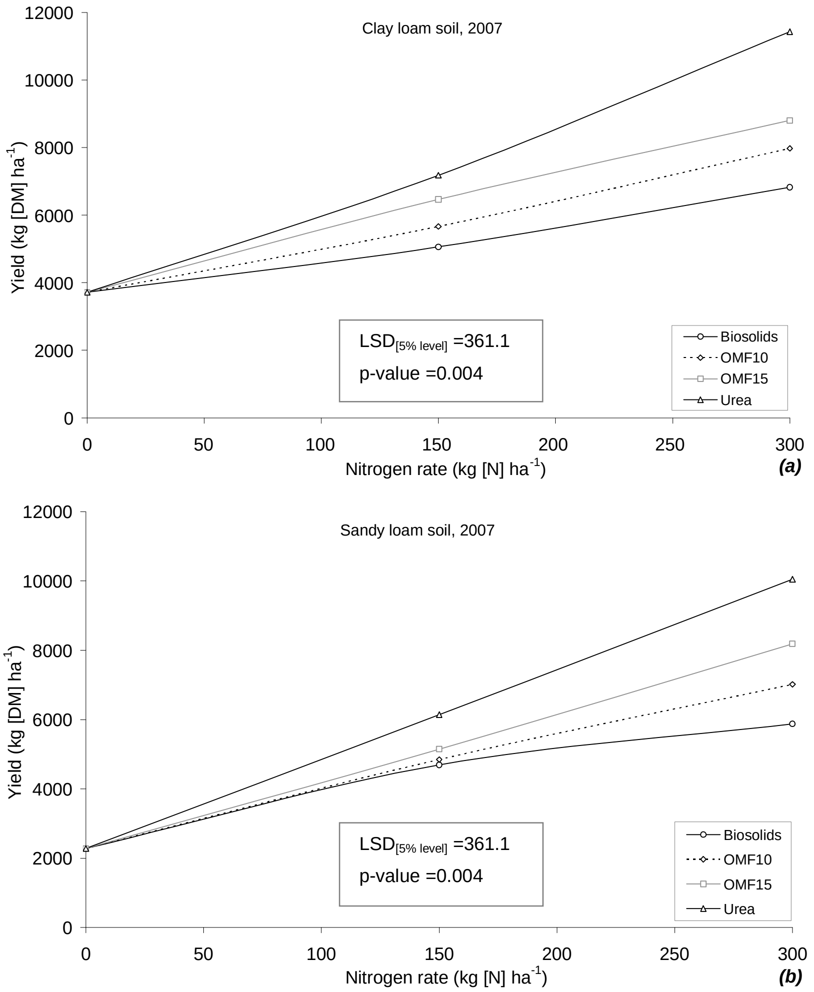


Figure 6.4: Relationships between the nitrogen application rate and dry matter yield for rye grass in 2007; (*a*) clay loam soil and (*b*) sandy loam soil (n=3).

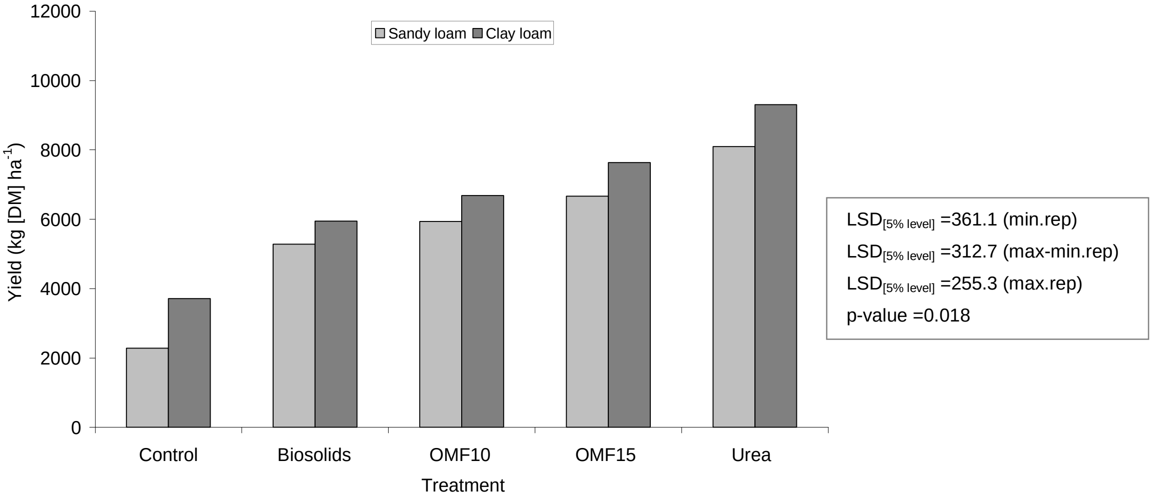


Figure 6.5: Mean dry matter yield of rye grass in controls (zero fertiliser) and treated pots on the sandy loam and the clay loam soils in 2007 for the two nitrogen rates used (n=6 except controls n=3).

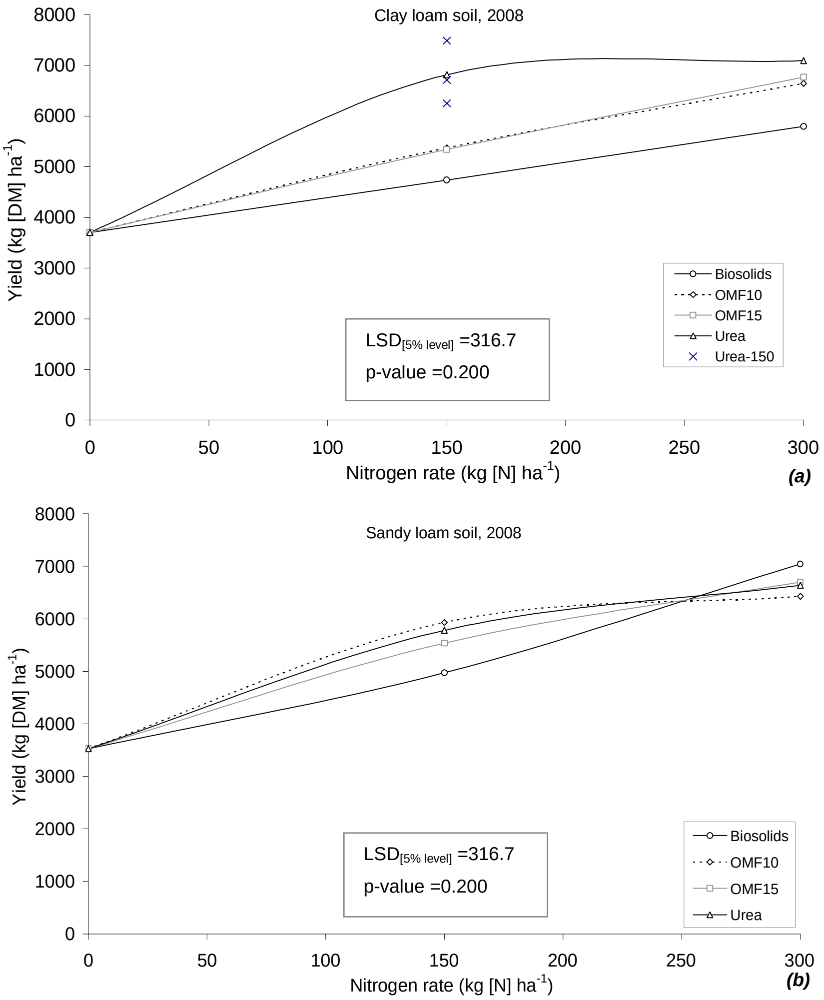


Figure 6.6: Relationships between the nitrogen application rate and dry matter yield for rye grass in 2008; (*a*) clay loam soil and (*b*) sandy loam soil (n=3).

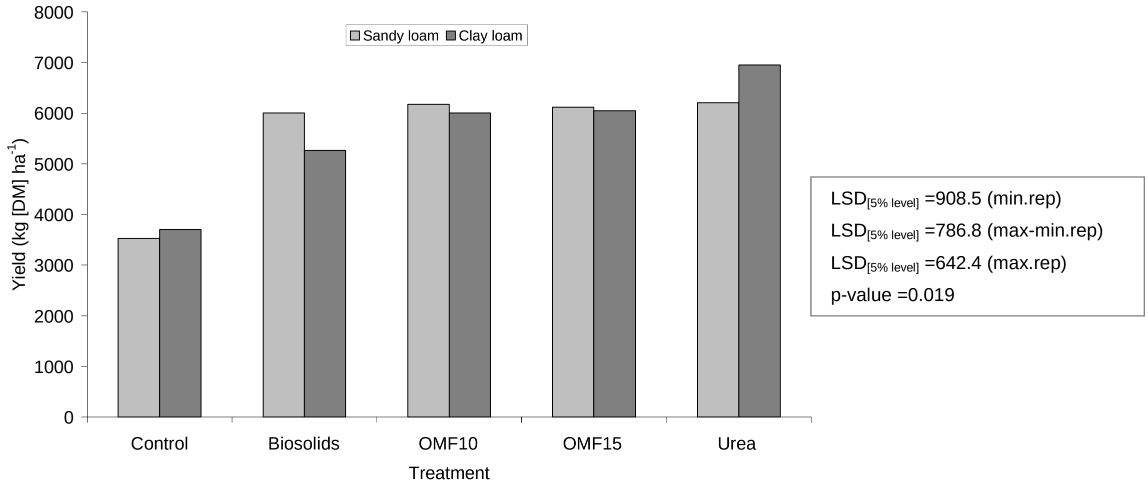


Figure 6.7: Mean dry matter yield of rye grass in controls (zero fertiliser) and treated pots on the sandy loam and the clay loam soils in 2008 for the two nitrogen rates used (n=6 except controls n=3).

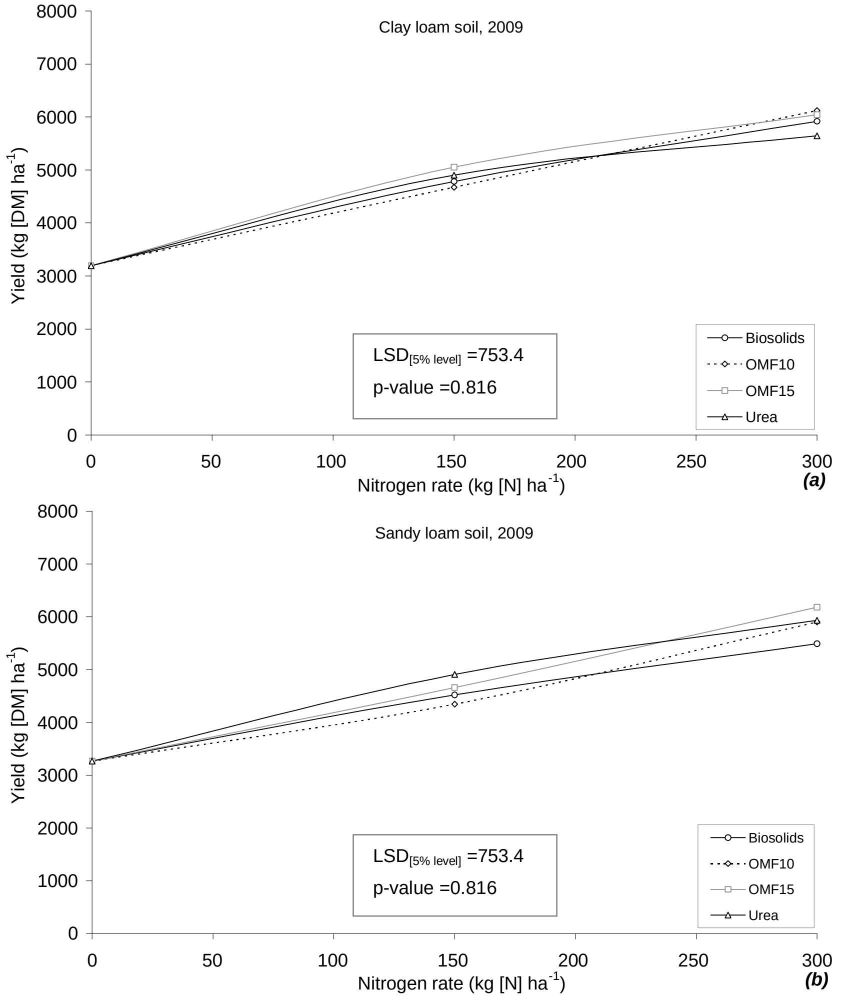


Figure 6.8: Relationships between the nitrogen application rate and dry matter yield for rye grass in 2009; (*a*) clay loam soil and (*b*) sandy loam soil (n=3).

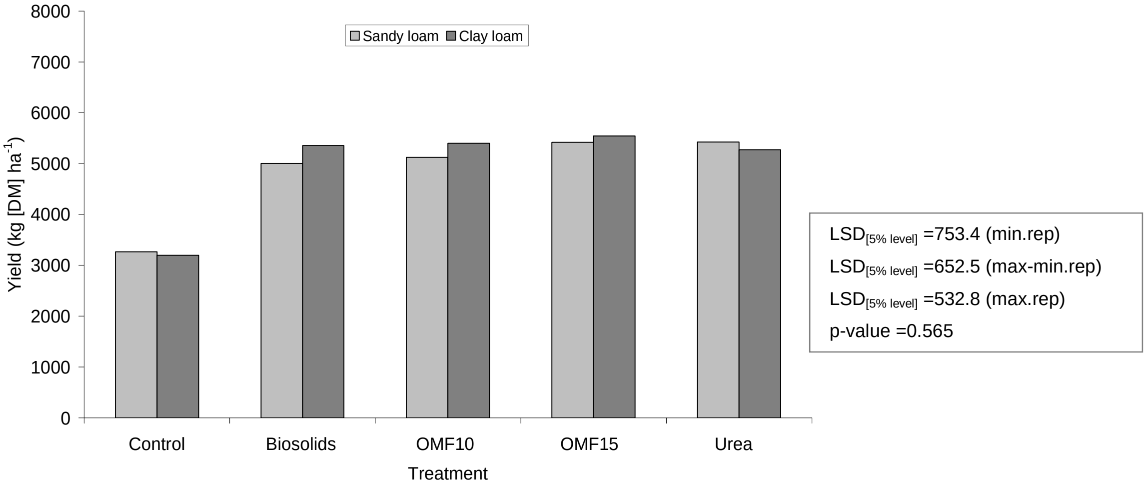


Figure 6.9: Mean dry matter yield of rye grass in controls (zero fertiliser) and treated pots on the sandy loam and the clay loam soils in 2009 for the two nitrogen rates used (n=6 except controls n=3).

Table 6.4: Linear regression analyses – relationships between dry matter yield and nitrogen application rate for 2007 (Figures 6.4a-b).

2007	------------- **Clay loam soil** -------------			------------- **Sandy loam soil** -------------		
Fertiliser	**Regression equation**	**R^2**	**p-value**	**Regression equation**	**R^2**	**p-value**
Biosolids	$y = 3642 + 10.37x$	0.98	<0.001	$y = 2483 + 12.0x$	0.94	<0.001
OMF$_{10}$	$y = 3654 + 14.20x$	0.97	<0.001	$y = 2345 + 15.79x$	0.99	<0.001
OMF$_{15}$	$y = 3782 + 16.96x$	0.98	<0.001	$y = 2250 + 19.69x$	0.99	<0.001
Urea	$y = 3582 + 25.73x$	0.99	<0.001	$y = 2269 + 25.91x$	0.99	<0.001

Table 6.5: Linear regression analyses – relationships between dry matter yield and nitrogen application rate for 2008 (Figures 6.6a-b).

2008	------------- **Clay loam soil** -------------			------------ **Sandy loam soil** ------------		
Fertiliser	**Regression equation**	**R^2**	**p-value**	**Regression equation**	**R^2**	**p-value**
Biosolids	$y = 3697 + 6.98x$	0.83	<0.001	$y = 3422 + 11.73x$	0.89	<0.001
OMF$_{10}$	$y = 3778 + 9.77x$	0.84	<0.001	$y = 3844 + 9.67x$	0.79	<0.001
OMF$_{15}$	$y = 3746 + 10.18x$	0.94	<0.001	$y = 3668 + 10.58x$	0.91	<0.001
Urea	$y = 4184 + 11.27x$	0.75	0.002	$y = 3759 + 10.38x$	0.76	0.001

Table 6.6: Linear regression analyses – relationships between dry matter yield and nitrogen application rate for 2009 (Figures 6.8a-b).

2009	------------ **Clay loam soil** -----------			------------- **Sandy loam soil** -----------		
Fertiliser	**Regression equation**	**R^2**	**p-value**	**Regression equation**	**R^2**	**p-value**
Biosolids	$y = 3270 + 9.08x$	0.79	<0.001	$y = 3312 + 7.42x$	0.88	<0.001
OMF$_{10}$	$y = 3632 + 8.03x$	0.96	<0.001	$y = 3186 + 8.78x$	0.94	<0.001
OMF$_{15}$	$y = 3771 + 7.76x$	0.84	<0.001	$y = 3244 + 9.72x$	0.93	<0.001
Urea	$y = 3788 + 6.45x$	0.87	<0.001	$y = 3367 + 8.90x$	0.89	<0.001

Fisher and Jewkes (2009) highlighted that the timing of the first nitrogen application to grass in the season is critical (in-field conditions) in order to obtain optimum dry matter yields and to avoid losses of nitrogen to the environment. In some cases, the T-sum =200 value; i.e. the sum of maximum daily temperatures recorded after January 1st, has been used with varying degree of success to assist in the decision to conduct the first N-dressing in grass crops (Fisher and Jewkes, 2009).

At this point in time, soil temperature is sufficiently high to optimise the response from the fertiliser applied. Such procedure could not be followed in the glasshouse studies as, given the scale of the experiment, it was necessary to allow sufficient time between cuts to ensure a reasonable amount of grass was produced in the pots to enable the required measurements and analyses to be conducted. It was also of interest to determine if there was a residual effect of the fertiliser (nitrogen) applied in the previous years by comparing dry matter yield in the first cut in subsequent years, prior to the first fertiliser application. The differences in dry matter yield recorded in the first cut in years two and three of the experiment did not show significant between the treatments for an $LSD_{[5\% \text{ level}]}$ value of 252.9. Therefore, a distinctive residual effect of the fertiliser type could not be observed up to the first cut in 2008 and 2009.

The various mathematical functions that are usually applied to describe the response of grass to the application of nitrogen will be reviewed in **Section 7.3.2**. In most circumstances, the response of the grass to the application of nitrogen has a linear component which is followed by a curvilinear section, and a section where yield may remain constant or start decreasing (Sparrow, 1979). In this respect, the work of Reid (1970), Sparrow (1979) and Morrison et al. (1980) indicated that grass' responses to the application of nitrogen are typically linear in the range of 0 to 300 kg [N] ha^{-1}.

Based on the work conducted in the field (**Chapter 7**) quadratic response curves were first fitted to the data obtained in the glasshouse (**Appendix A.6.4**) which showed that in most cases, the estimate of the parameters for the square term (quadratic function) was not significant (t_{pr}>0.05). This had also been observed for the grass grown in the field treated with biosolids but because their square terms were found to have negative coefficients, it was decided to fit a quadratic function instead which enabled the derivation of the terms Y_{max} (maximum dry matter yield) and Y_{10} (optimum dry matter yield) and their corresponding N_{max} (nitrogen rate required for Y_{max}) and N_{10} (nitrogen rate required for optimum yield) respectively from the equations. These relationships are examined in **Chapter 7** for the data reported for the field studies. The grass yield data obtained in the glasshouse, in general, did not permit the use of quadratic functions to describe the relationship with nitrogen application rate. This observation is in close agreement with those made by Sparrow (1979) and Morrison et al. (1980) as highlighted above; despite their work was conducted in the field. For the range of nitrogen application rates used in the glasshouse (0-300 kg [N] ha^{-1}), these relationships were better explained by linear functions which, as indicated above, were justified on the basis that the square terms of the response functions were nonsignificant (t_{pr}>0.05) in most cases.

An exception to this was the response encountered to the application of urea in 2008 on the clay loam soil which was better explained by a quadratic function instead. However, in most circumstances, the regression coefficients for the square terms were positive; hence, a 'peak' in the response curves could not be determined in the range of nitrogen applications rates investigated. In all cases, the R^2 indicated acceptable fits of the linear models ($R^2 \geq 0.75$).

It is important to acknowledge that in the glasshouse, the response functions were obtained with lesser number of points compared with the field. Therefore, a more complete response curve could not be drawn with the data available which could be affecting the type of response curve fitted. The increments in dry matter yield for every additional unit of nitrogen added is given by the slope of the linear regression functions shown in **Tables 6.4-6.6**. These showed increments (kg [DM] ha^{-1} per kg of additional N) in the range of *c*.7 to 12 (biosolids), *c*.8 to 16 (OMF_{10}), *c*.8 to 20 (OMF_{15}) and *c*.6.5 to 26 (urea), depending upon the soil type and the year. In general, these increments and the differences between the treatments tended to be smaller in years two and three of the experiment compared with the year of establishment – possibly related to the concentration of urea-N in the fertiliser and the method of application.

The analysis of variance for the data corresponding to **2007** showed that there were significant differences ($p<0.001$) in dry matter yield between the two soil types. The clay loam soil produced on average *c*.1000 kg [DM] ha^{-1} more than the sandy loam soil in the first year which reflected the overall higher fertility status of the former soil compared to the later. There were also significant differences between the unfertilised controls and the treatments ($p<0.001$) and the effect was observed in both soil types ($p=0.007$).

Overall, the application of fertiliser in 2007 increased the production of dry matter by *c*.4000 kg ha^{-1} compared with the controls (zero fertiliser). When comparing the controls versus the treatments, the sandy loam soil showed overall a higher increase in the production of dry matter (from 2278 to 6495 kg [DM] ha^{-1}) than the clay loam soil (from 3713 to 7390 kg [DM] ha^{-1}) which reflected the higher response to the applied fertiliser in the first soil ($LSD_{[5\% \text{ level}]}$ =270.8). This higher response in the sandy loam soil was also expected given its overall lower (initial) fertility compared with the clay loam soil. Significant differences in dry matter yield were also found with respect to the fertiliser type, the nitrogen application rate and the interaction between the two factors (p-values <0.001).

On average, across the whole experiment, the use of OMF_{10} and OMF_{15} increased the production of dry matter in 2007 by *c*.12.5% and *c*.27.5% respectively compared with biosolids whereas for urea this increase was *c*.55% (**Figure 6.5**).

The production of dry matter during the first year of the trial was found to increase with the concentration of nitrogen in the fertiliser applied and, in particular, with the concentration of readily available nitrogen. In addition, when the nitrogen application rate was increased from 150 to 300 kg [N] ha^{-1}, the increase in dry matter yield was found to be significantly higher with the use of more concentrated nitrogen products. These observations help to explain the significance in the interaction between the fertiliser type and the nitrogen rate indicated above. In this respect, the results obtained from the plots experiment (rye grass) in the field appeared to be consistent with those of the glasshouse.

The analysis of variance for the data corresponding to **2008** did not show a significant effect ($p=0.823$) between the two soil types. However, as reported for 2007, in the second year of the studies, a significant difference ($p<0.001$) in dry matter yield was encountered between the unfertilised controls and the treatments. The application of fertiliser increased the production of dry matter by *c*.2500 kg ha^{-1} compared with the controls which was substantially lower than the overall increase recorded in the treated pots in the first year. In addition, in both soil types, fertilised pots produced approximately the same level of increments in dry matter yield compared with the controls (from 3526 to 6129 kg [DM] ha^{-1}, and 3701 to 6070 kg [DM] ha^{-1} for the sandy loam and the clay loam soils respectively; $LSD_{[5\% \text{ level}]}$ =681.4; $p=0.626$). Overall, in 2008, significant differences in dry matter yield were found with respect to the fertiliser type ($p=0.002$) and the nitrogen application rate ($p<0.001$); however, the interaction between the two factors was found to be nonsignificant ($p=0.142$).

The differences in dry matter yield encountered as a result of the fertiliser type used were observed in both soils ($p=0.019$) but this effect was mainly due to the use of urea which showed a relatively improved performance compared with the other fertilisers materials, especially on the clay loam soil fertilised with 150 kg [N] ha^{-1}. On average, across the whole experiment, the use of OMF_{10} and OMF_{15} increased the production of dry matter in 2008 by *c*.8% respectively compared with biosolids whereas for urea this increase was *c*.17% (**Figure 6.7**). It is important to highlight that the differences in dry matter yield indicated above were substantially smaller than those obtained in 2007.

A possible explanation may be with regards to the surface-application of the fertilisers in 2008 affecting their overall performance, possibly, as a result of volatilisation of ammonia under the prevailing experimental conditions. This was more evident for the pots treated with OMF_{15} and urea which showed a larger decrease in the production of dry matter compared with OMF_{10} and biosolids in the second year of the trials (from 7149 to 6085 kg [DM] ha^{-1} for OMF_{15} and from 8700 to 6583 kg [DM] ha^{-1} for urea in 2007 and 2008 respectively).

Similarly, in **2009**, the differences in dry matter yield between the two soil types were nonsignificant (p=0.315) but there was, overall, a significant effect of the treatments compared with the controls (p<0.001). There was, as expected, a significant effect of the nitrogen rate on the yield (p<0.001) which was not observed for the fertiliser type (p=0.410) and the same was true when factoring in the effect of the soil type with respect to both the nitrogen rate and also the fertiliser type (p-values of 0.565 and 0.476 respectively).

As can be seen from **Figures 6.5**, **6.7** and **6.9**, there was a progressive decline in biomass production overtime (*c*.15% year on year, on average, across the whole experiment). To a limited extent, this could be due to a small reduction in the plants' population in the pots which was noticed in the periphery of the pots and in the proximity of the inner wall (≈20 mm). This effect could be the result of continuous deposition of salt on the edges of the pots originated from the evaporation of irrigation water. It was found to occur in all pots to a similar extent; therefore, an appreciable differential effect (as determined by visual assessment) on the treatments may be discarded.

The repeated measurement analysis of variance was conducted to compare the effects of the treatments on the annual dry matter yield data over the three years period. This indicated that, overall, there were significant differences (p<0.001) with respect to the fertiliser type and the same was observed when factoring in the time (p=0.045). However, there was an overall decline in the production of dry matter overtime and the differences encountered between the fertiliser types became progressively smaller from the start of the experiment. Indeed, in 2009, all fertiliser materials resulted in very similar levels of biomass production (mean values across the whole experiment were in the range of 5178 to 5483 kg [DM] ha^{-1}; $LSD_{[5\% \text{ level}]}$ =367.3). This is an important aspect which was not observed in the field studies where the differences in dry matter yield between the biosolids and the other fertiliser materials were more evident; i.e. OMF_{10}, OMF_{15} and urea showed overall consistently higher performance in-field conditions than biosolids.

In the glasshouse, however, biomass production in biosolids-treated pots remained relatively stable ranging from 5613 to 5178 kg [DM] ha^{-1} between 2007 and 2009. Based on these observations, it is possible to suggest the following:

- Dry matter yield was affected by the fertiliser application method whether it was soil-incorporated (2007) or surface-applied (2008 & 2009),
- The larger decline in dry matter yield in OMF- and urea-treated pots compared with those amended with biosolids between 2007 and 2009 were possibly due to losses of nitrogen by volatilisation which could have reduced the efficiency of urea-containing fertilisers,
- The decline in dry matter yield overtime was also larger in urea than OMF$_{15}$ and OMF$_{10}$ respectively; therefore, losses of ammonia by volatilisation could be related to the concentration of urea-N in the fertiliser,
- The conditions in the glasshouse could have enhanced both processes simultaneously; the mineralisation of biosolids-N (including the organic-N fraction in the OMF), and volatilisation of ammonia from OMF$_{10}$, OMF$_{15}$ and urea. Consequently, the levels of dry matter yield recorded in biosolids-treated pots were comparatively more sustained over the years; i.e. they did not fall to the same extent as OMF$_{10}$-, OMF$_{15}$- and urea-treated pots,
- The decline in dry matter yield in 2008 and 2009 compared with 2007 could be also associated with the timing of fertiliser application in relation to the maximum growth period of grass (see **Section 6.4**).

Air temperatures inside the glasshouse (**Appendix A.6.7**) recorded in parallel studies at Cranfield University (Ghalamboran, 2011; Giné-Bordonaba, 2010; Giné-Bordonaba and Terry, 2010) indicated that the mean temperature between April and July in 2009 was 22.5°C (mean temperature's range of 21.0 to 23.0°C). The mean air temperature (Met Office, 2010) between April and July for the years 2007-09 (**Appendix A.7.1**) was 14.1°C (mean temperature's range of 8.9 to 19.0°C) which suggests that during this time of the year, temperatures inside the glasshouse can be, on average, up to 60% higher than outside. Since the soils were maintained with relatively good moisture conditions it is reasonable to state that the mineralisation of biosolids-N (including the organic-N fraction in the OMF granule) had benefitted from these conditions. Hence, a larger supply of nitrogen to the crop from the organic-N fraction in the fertiliser materials could have occurred in the glasshouse compared with the field which helps explaining the stability observed in dry matter yield in these pots.

In addition, higher air temperatures in the glasshouse combined with surface application of urea-containing fertilisers also suggests that the chances for volatilisation of ammonia were higher than those of the field. Another feature is that in 2007, the pots were maintained in the glasshouse at Cranfield University (Silsoe) which has ventilation on the side-walls and also on the roof (**Appendix A.6.1**) favouring cooling and, possibly, contributing to reduce the rate of respiration. The repeated measurement analysis of variance also indicated that the interaction between the time and the soils was significant ($p<0.001$) but the effect was largely due to the results of dry matter yield obtained in 2007. In the first year, the clay loam soil produced consistently higher dry matter than the sandy loam soil as highlighted earlier (*c.*+1000 kg [DM] ha^{-1}) whereas in the second and third years, biomass production reached approximately the same level in both soils types (*c.*5800 and *c.*5100 kg [DM] ha^{-1} for 2008 and 2009 respectively).

It is expected that in the first year, and following the establishment of the experiment, large amounts of soil mineral nitrogen had been released as a result of the soil disturbance occurred during the preparation of the pots; especially, in the clay loam soil which had more organic matter. In the following years, there appeared to be an important effect of the crop upon the soil in relation to the increase in the level of soil organic matter in the sandy loam soil (see **Section 6.3.3-v**). Hence, the sandy loam soil was able to release sufficient amounts of nitrogen to sustain similar levels of dry matter yield as those obtained for the clay loam soil. It is important to highlight that under such experimental conditions and having the same water/irrigation regimes and fertilisation levels these differences between the soils were reduced.

6.3.2 Nitrogen in harvested plant material, nitrogen uptake and nitrogen use efficiency

The concentration of nitrogen in harvested plant material (TN_{plant}) was determined for each of the cuts performed during 2008 and 2009 according to the method indicated in **Table 6.2**. Following the procedure adopted by Kokkora (2008), this value was subsequently multiplied by the corresponding value of dry matter yield to obtain the total nitrogen uptake per cut. The sum of the nitrogen uptake for the three cuts conducted each year was taken as equivalent to the total nitrogen uptake (TN_{uptake}). This value was used for the estimation of the nitrogen use efficiency (NUE) of applied nitrogen fertiliser. Total nitrogen in harvested plant material (TN_{plant}) is reported as percentage by weight (%, w w^{-1}) and nitrogen uptake (TN_{uptake}) is reported in kg [N] ha^{-1}.

i. Nitrogen in harvested plant material

The results obtained for TN_{plant} are shown in **Figure 6.10**. The statistical analysis indicated that, overall, there were significant differences ($p<0.001$) between the two soil types and that the clay loam soil produced approximately 5% higher TN_{plant} than the sandy loam soil. In both soil types, the control pots showed significantly lower ($p=0.013$) TN_{plant} than the treated-pots. Overall, the application of fertiliser increased TN_{plant} by *c*.13% compared with the controls (mean values of TN_{plant} were 1.81% and 2.04% [w w^{-1}] for the control and the treatments respectively; $LSD_{[5\% \text{ level}]}$ =0.0626). There was also a significant effect of the fertiliser type ($p<0.001$), the nitrogen application rate ($p<0.001$) and the interaction between the two factors ($p=0.002$). In general, TN_{plant} was found to increase with the concentration of readily available nitrogen in the fertiliser with biosolids showing consistently lower values of TN_{plant} than the other fertilisers used. OMF_{10} and OMF_{15} resulted in intermediate levels of TN_{plant} between biosolids and urea (mean values of TN_{plant} were 1.97%, 2.01% and 2.15% [w w^{-1}] for biosolids, OMF_{10} and OMF_{15}, and urea respectively; $LSD_{[5\% \text{ level}]}$ =0.059). With respect to the nitrogen application rate, TN_{plant} showed an increase of 0.16% N [w w^{-1}], on average, for every 150 kg [N] ha^{-1} applied.

The differences in TN_{plant} between-years were greater ($p<0.001$) in the sandy loam than the clay loam soil which could be associated with larger nitrogen supply (and higher level of SOM) in the latter soil. As can be seen from the graph, the effect of the interaction between the nitrogen rate and the fertiliser type was largely due to the increase in TN_{plant} obtained with the use of urea at 300 kg [N] ha^{-1}. The differences recorded between OMF_{10} and OMF_{15} were nonsignificant, on average, over the range of nitrogen application rates and soil types (mean values of 2.01% [w w^{-1}]; $LSD_{[5\% \text{ level}]}$ =0.0586). In addition, both OMF produced significantly higher levels of TN_{plant} than biosolids at the two nitrogen rates used (mean value for biosolids was 1.97% [w w^{-1}] for the same LSD-value mentioned above).

It is important to note that the increase in the concentration of nitrogen in plant with the nitrogen application rate occurred despite the overall increase in dry matter yield encountered at higher fertilisation levels. The concentration of nitrogen in harvested plant material was found to be significantly different depending on the timing of the cut was performed ($p<0.001$). In general, TN_{plant} increased markedly in the first cut following the application of fertiliser and the effect was observed in both soil types ($p<0.001$). The fertiliser type also showed a significant effect ($p<0.001$) with respect to the controls when factoring in the time (**Figure 6.11**).

This implied that the various fertiliser types used resulted in different nitrogen concentrations in plant at different times of the year which can explain differences in the ability of the fertiliser to release nitrogen. This effect was however largely due to the differences in TN_{plant} encountered in the first cut in 2007 and similar results were observed with respect to the data shown for dry matter yield, as discussed in **Section 6.3.1**.

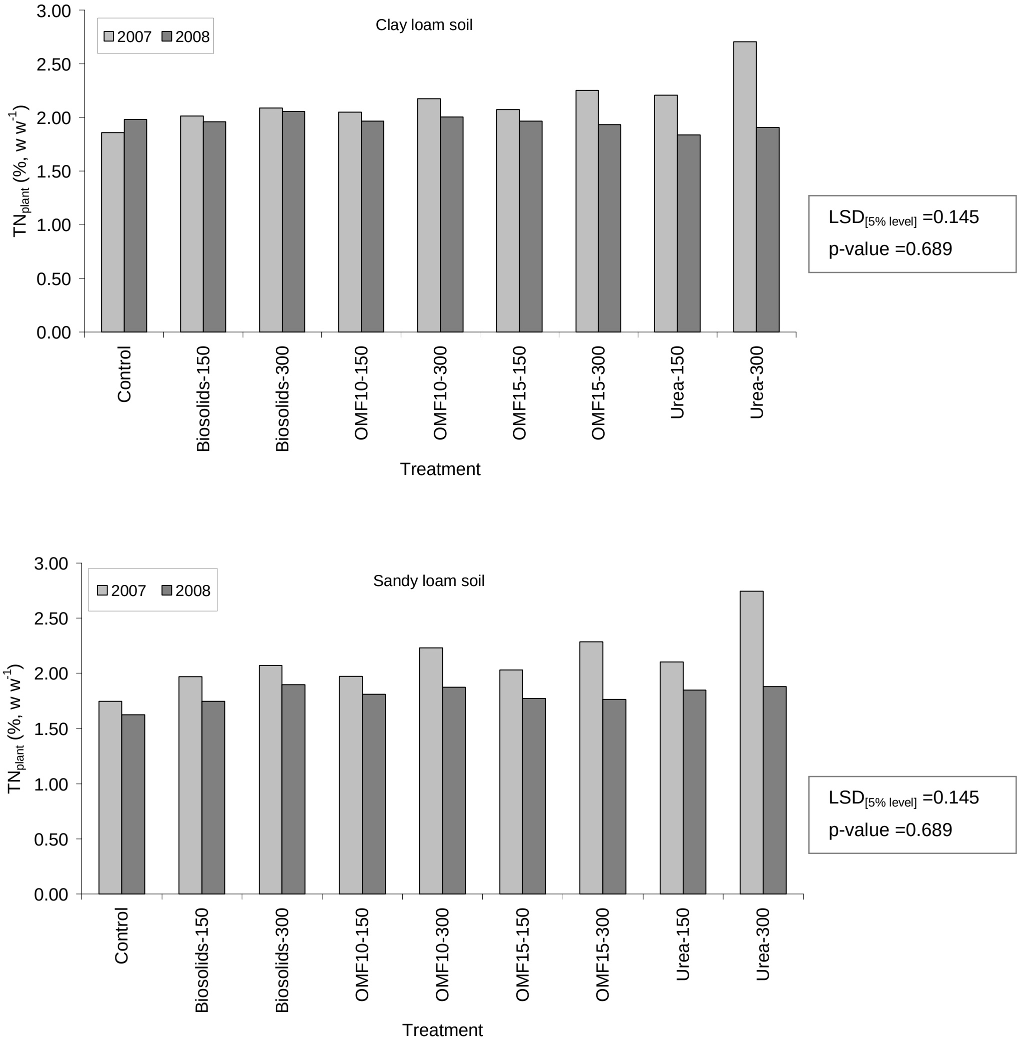


Figure 6.10: Mean TN_{plant} in rye grass for the various fertiliser types used in the glasshouse studies; (*a*) Clay loam, (*b*) Sandy loam. Values of TN_{plant} for each treatment correspond to the mean value for the three cuts conducted each year (n=9).

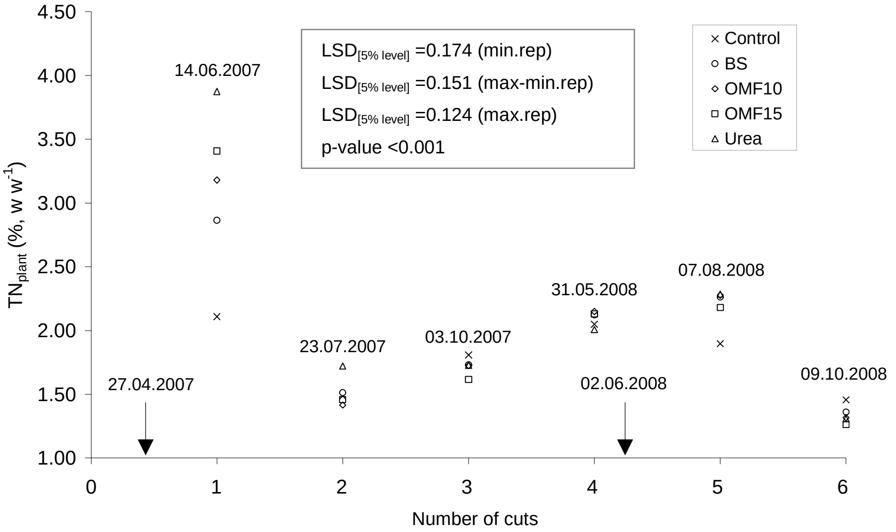


Figure 6.11: Relationship between the timing of cut and TN$_{plant}$ for the various fertiliser types used in the glasshouse studies. Values of TN$_{plant}$ for each treatment correspond to the mean value of the two soil types for the first two years of the study. The arrows indicate the date the fertilisers were applied.

As can be seen in the figure above, the values of TN$_{plant}$ encountered in the 3rd and 6th cuts for the controls, tended to be higher than the treatments. It is possible that because of the lower dry matter yield produced each year in the 3rd cut in the control pots, the concentration of nitrogen in-plant was higher.

ii. Nitrogen uptake

The estimated values of nitrogen uptake for the grass crop in 2007 and 2008 are shown in **Figures 6.12a-b**. The figures show the total nitrogen uptake for the year and also that estimated for each of the three cuts conducted per year. The mean values of TN$_{uptake}$ obtained for each of the fertiliser treatments in the two soil types were subsequently regressed (simple linear regression analysis) against the nitrogen application and the relationships encountered are shown in **Figures 6.13a-b**. The regression equations, R^2 and the p-values are presented in **Table 6.7** for both years. In general, the R^2 values encountered indicated acceptable fits for the linear models (≥0.80). In **2007** (**Figure 6.12a**), significant differences in TN$_{uptake}$ were found between the two soil types, the control and the treatments, the fertiliser types, the nitrogen application rates, and the interaction between the fertiliser type and the rate used (p-values <0.001). With respect to the fertiliser type, nitrogen uptake was related to the concentration of available nitrogen in the fertiliser. In both soil types, urea-treated grass showed the highest nitrogen uptake (232 kg [N] ha^{-1} – mean value of TN$_{uptake}$ for the two soil types).

The values of nitrogen uptake obtained for OMF_{10} and OMF_{15} ranged from 148 to 170 kg [N] ha^{-1} (mean value for the two soil types) which were, approximately, 20% to 40% higher than that of the biosolids-treated grass respectively. With regards to the nitrogen application rate, the regression analysis for **2007** (**Figure 6.13a**) showed that TN_{uptake} was significantly correlated ($p<0.001$) with the level of nitrogen fertilisation and the effect was observed in all fertiliser treatments. The slope of the regression line was also increased with the use of a more concentrated nitrogen product; in particular, the uptake of urea-N applied at 300 kg [N] ha^{-1} was significantly enhanced compared with the rest of the treatments at the same level of fertilisation (*c*.1.7 and *c*.1.5 times higher than OMF_{10} and OMF_{15} respectively). TN_{uptake} was also significantly higher (*c*.12-15%) in OMF_{15} than OMF_{10} despite both materials were produced with similar nitrogen contents in 2007 as reported in **Chapter 3**.

Similarly, in **2008** (**Figure 6.12b**), significant differences in TN_{uptake} were found between the control and the treatments ($p<0.001$), the fertiliser types ($p=0.017$) and the nitrogen application rates ($p<0.001$). Overall, however, the differences encountered between the two soil types were nonsignificant ($p=0.118$) and the same effect (nonsignificant) was observed for the interaction between the fertiliser type and the nitrogen rate ($p=0.163$). With respect to the fertiliser type, both OMF products showed, on average, intermediate levels of TN_{uptake} (ranging from 110 to 135 kg [N] ha^{-1}) between those of biosolids (range 97-128 kg [N] ha^{-1}) and urea (126-140 kg [N] ha^{-1}). This effect was also reflected on the slope of the regression lines (**Figure 6.13b**) which were almost parallel. It can also be seen from **Figures 6.12a-b** that nitrogen uptake by the crop was increased markedly following the application of the fertiliser. As a result there was a significant effect of the time ($p<0.001$) on the nitrogen uptake by the crop; i.e. nitrogen uptake differed significantly between cuts. The effect was more obvious in 2008 when the fertiliser was applied after the first cut was performed at the beginning of the season (see also **Figure 6.11**).

The majority of the nitrogen was taken up between the date of fertiliser application and the subsequent cut. However, for biosolids, nitrogen uptake between the second and the third cuts represented a larger proportion of the total uptake compared with the rest of the fertiliser treatments. This leads to the fact that the release of nitrogen from the biosolids requires more time; hence, it progressed to a further extent into the season compared with the other fertilisers. The percentage of the TN_{uptake} taken up in the 3rd cut represented, on average, 18.25% for biosolids (range 12.9-23.6%), 14.5% for OMF_{10} (range 12.5-16.4%), and 12.9% for OMF_{15} and urea (range 10.5-15.3%).

It is also interesting to note that in 2008, the level of N_{uptake} recorded for all treatments up to the 1st cut (including the controls) was almost identical (ranging from 36 to 43 kg [N] ha^{-1}). This suggested that the availability of nitrogen to crop up to the 1st cut was not significantly affected by the type of fertiliser used. It also suggested that fertiliser-N (in biosolids and OMF) mineralised between the 3rd cut in 2007 and the 1st cut in 2008 had undergone immobilisation. As a result, nitrogen availability before the 1st cut was more dependent on the mineralisation of soil organic nitrogen rather than the supply from the fertiliser. These observations were also consistent with the results of dry matter yield and TN_{plant} encountered in the 1st cut in 2008, and those of dry matter yield found for 2009; where all treatments performed at approximately the same level for the three measured parameters.

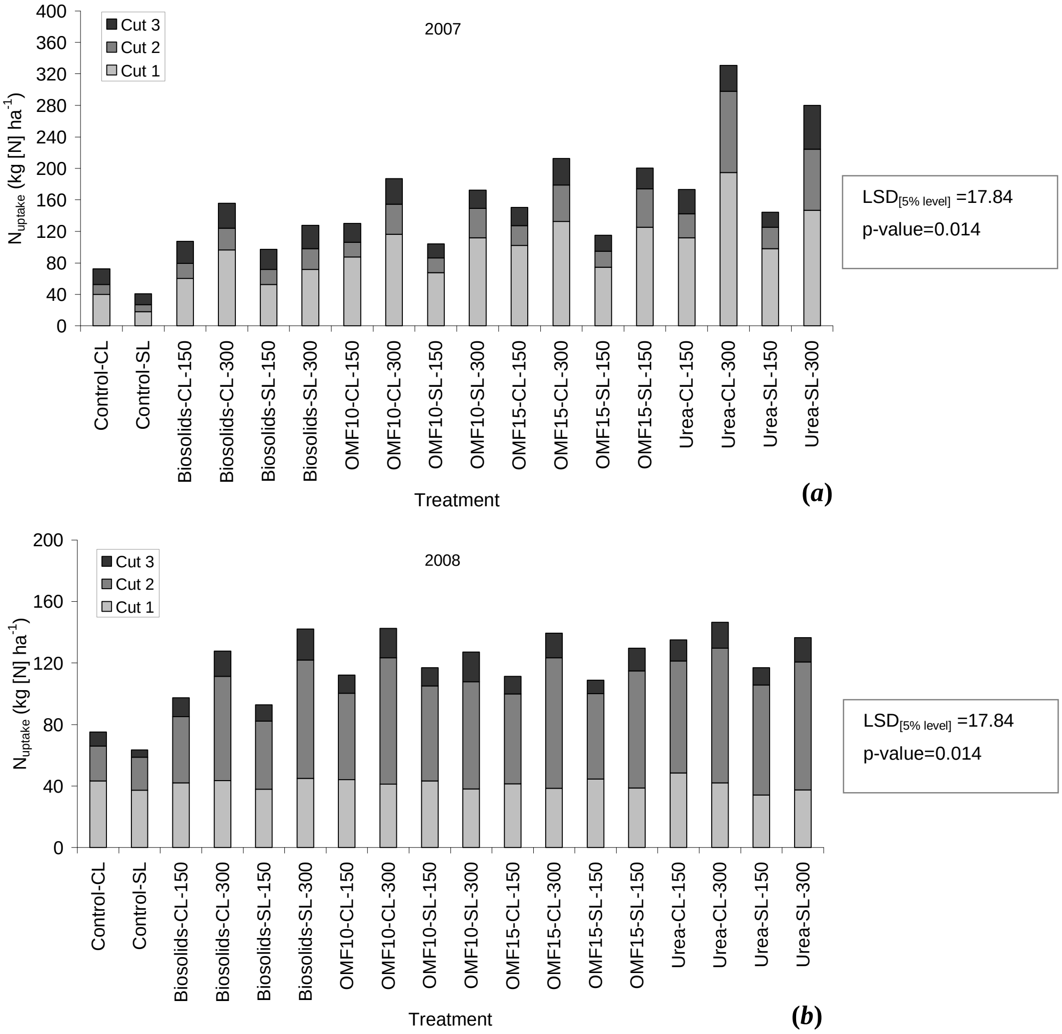


Figure 6.12: Nitrogen uptake by rye grass showing the totals for the year and the nitrogen uptake for individual cuts; (*a*) – 2007, and (*b*) – 2008 [CL: clay loam; SL: sandy loam].

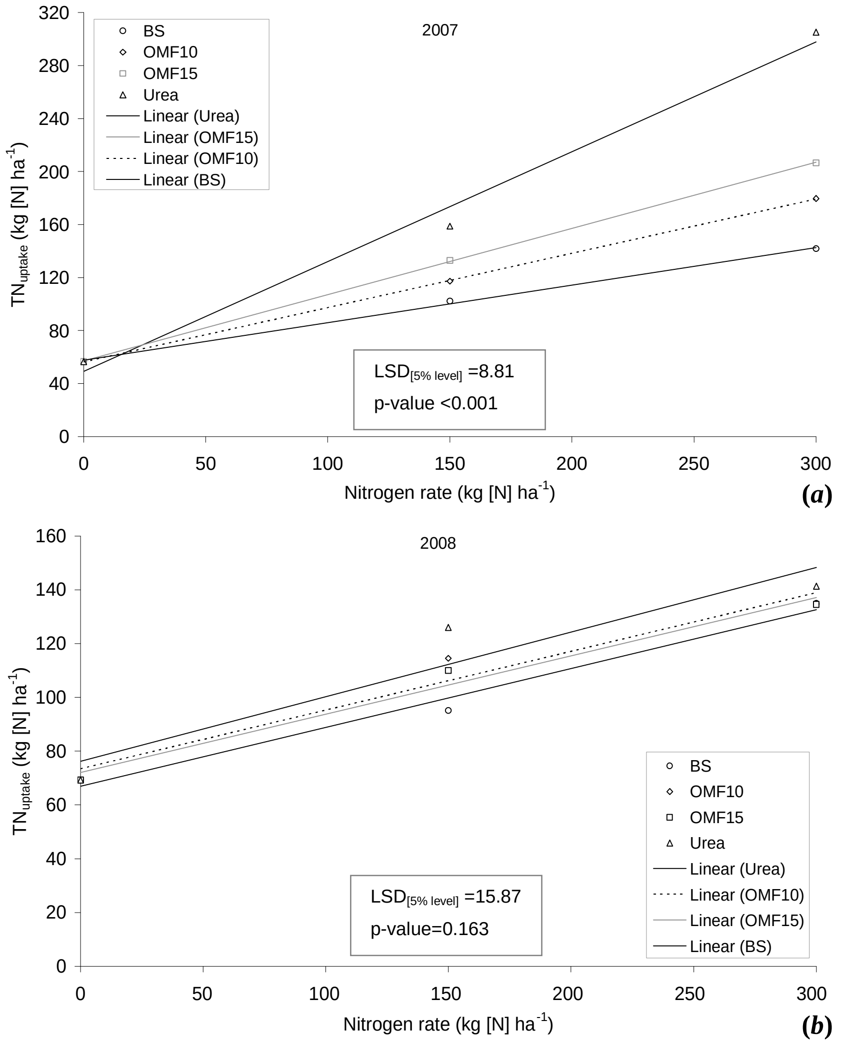


Figure 6.13: Relationship between the nitrogen application rate and TN_{uptake} of rye grass for the four fertiliser types used in the glasshouse studies; (*a*) – 2007, and (*b*) – 2008. The values of TN_{uptake} correspond to the mean value obtained for the two soil types for each fertiliser treatment (n=6). BS: biosolids granules.

Table 6.7: Linear regression analyses – relationships between nitrogen application rate and TN_{uptake} for 2007 and 2008 (Figures 6.13a-b).

Year	**2007**			**2008**		
Fertiliser	**Regression equation**	**R^2**	**p-value**	**Regression equation**	**R^2**	**p-value**
Biosolids	$y = 57.59 + 0.284x$	0.98	<0.001	$y = 66.98 + 0.219x$	0.94	<0.001
OMF_{10}	$y = 56.28 + 0.410x$	0.99	<0.001	$y = 73.47 + 0.218x$	0.85	<0.001
OMF_{15}	$y = 52.12 + 0.479x$	0.98	<0.001	$y = 72.41 + 0.201x$	0.81	<0.001
Urea	$y = 48.18 + 0.823x$	0.98	0.002	$y = 76.19 + 0.241x$	0.86	<0.001

As highlighted for dry matter yield, the slope of the regression equations shown in the table above indicate the expected increment in TN_{uptake} for every additional unit of nitrogen applied. It can be seen from the table that in the first year these increments tended to be higher in the products that had a larger concentration of readily available nitrogen in its composition whereas in 2008, the slope of the regression lines were of similar order of magnitude.

iii. Nitrogen use efficiency

Nitrogen use efficiency (NUE) was estimated using the difference method (Cassman et al., 1998; Johnston and Poulton, 2009). The results obtained are reported in **Table 6.8** in two ways which are the agronomic efficiency (A_E) and the apparent recovery (R_N) of applied nitrogen; both terms were defined earlier in **Chapter 2**. The A_E estimates NUE based on the yield of the crop in relation to the nitrogen application rate whereas R_N expresses NUE based on the nitrogen uptake by the crop and the nitrogen application rate used. Analyses of TN_{plant} were conducted for all six cuts performed between 2007 and 2008; therefore, estimates of R_N are not presented for 2009.

The results of the statistical analysis indicated that NUE, as determined by the apparent nitrogen recovery (R_N), was statistically higher ($p=0.007$) in the sandy loam compared with the clay loam soil although the difference was small (mean values of 38.7% and 35.5% respectively; $LSD_{[5\% \text{ level}]}$ =2.23). This effect was possibly due to the relatively larger supply of SMN in the latter soil. There were also significant differences in R_N with respect to the fertiliser type ($p<0.001$) which were observed in both soil types ($p=0.035$). However, the differences in R_N encountered overall as a result of the nitrogen rate used or the interaction between the rate and the fertiliser type were nonsignificant (p-values of 0.296 and 0.262 respectively). The differences in R_N recorded between-years were also significant ($p<0.001$) – R_N accounted for 49% in 2007 and 25.2% in 2008 – mean values across the whole experiment respectively.

Overall, both OMF products resulted in intermediate levels of nitrogen recoveries (mean values in the range of 33.4% to 37.4%) between those encountered for biosolids- and urea-treated grass (mean values of 24.5% and 53.2% respectively; $LSD_{[5\% \text{ level}]}$ =3.16). The overall decrease observed in R_N in 2008 compared with 2007 appeared to have been related to the concentration of urea-N in the fertiliser; e.g. the recovery of nitrogen in urea-treated pots decreased from *c*.75% on average in 2007 to *c*.31% in 2008 whereas for biosolids-treated pots the decrease was from *c*.29% in 2007 to *c*.20% in 2008.

Table 6.8: Nitrogen use efficiency of applied N-fertiliser in rye grass between 2007 and 2009 as calculated by the difference method – A_E: agronomic efficiency; R_N: N-recovery [Use LSD$_{[5\% \text{ level}]}$ =8.64 for R_N (p=0.016); and LSD$_{[5\% \text{ level}]}$ =3.58 for A_E (p=0.152)].

2007	**-------------------------- Nitrogen use efficiency --------------------------**					
Soil type	**Clay loam**			**Sandy loam**		
Biosolids-N (kg ha^{-1})	**0**	**150**	**300**	**0**	**150**	**300**
Yield (kg [DM] ha^{-1})	3713.1	5057.9	6823.8	2278.5	4692.4	5877.1
A_E (kg [DM] kg^{-1} [N])	-	8.97	10.37	-	16.09	12.00
R_N (%)	-	23.27	27.73	-	37.47	29.00
OMF$_{10}$-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3713.1	5664.3	7973.2	2278.5	4847.4	7016.4
A_E (kg [DM] kg^{-1} [N])	-	13.01	14.20	-	17.13	15.79
R_N (%)	-	38.60	38.17	-	42.27	43.83
OMF$_{15}$-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3713.1	6464.5	8800.3	2278.5	5147.2	8186.0
A_E (kg [DM] kg^{-1} [N])	-	18.34	16.96	-	19.12	19.69
R_N (%)	-	52.07	46.70	-	49.60	53.23
Urea-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3713.1	7178.7	11430.9	2278.5	6138.8	10051.3
A_E (kg [DM] kg^{-1} [N])	-	23.10	25.73	-	25.74	25.91
R_N (%)	-	67.33	86.07	-	68.93	79.77

2008	**-------------------------- Nitrogen use efficiency --------------------------**					
Soil type	**Clay loam**			**Sandy loam**		
Biosolids-N (kg ha^{-1})	**0**	**150**	**300**	**0**	**150**	**300**
Yield (kg [DM] ha^{-1})	3700.5	4736.7	5793.8	3526.5	4973.0	7045.1
A_E (kg [DM] kg^{-1} [N])	-	6.91	6.98	-	9.64	11.73
R_N (%)	-	14.89	17.50	-	19.60	26.23
OMF$_{10}$-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3700.5	5371.7	6643.4	3526.5	5929.6	6426.3
A_E (kg [DM] kg^{-1} [N])	-	11.14	9.81	-	16.02	9.67
R_N (%)	-	24.60	22.43	-	35.73	21.17
OMF$_{15}$-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3700.5	5336.8	6766.2	3526.5	5537.4	6700.8
A_E (kg [DM] kg^{-1} [N])	-	10.91	10.22	-	13.41	10.58
R_N (%)	-	24.07	21.43	-	30.27	22.07
Urea-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3700.5	6814.8	7093.7	3526.5	5781.8	6640.0
A_E (kg [DM] kg^{-1} [N])	-	20.76	11.31	-	15.04	10.38
R_N (%)	-	39.93	23.73	-	35.67	24.37

2009	**-------------------------- Nitrogen use efficiency --------------------------**					
Soil type	**Clay loam**			**Sandy loam**		
Biosolids-N (kg ha^{-1})	**0**	**150**	**300**	**0**	**150**	**300**
Yield (kg [DM] ha^{-1})	3193.7	4784.3	5919.1	3264.6	4520.4	5489.7
A_E (kg [DM] kg^{-1} [N])	-	10.60	9.08	-	8.37	7.42
OMF$_{10}$-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3193.7	4675.7	6122.6	3264.6	4346.3	5899.5
A_E (kg [DM] kg^{-1} [N])	-	9.88	9.76	-	7.21	8.78
OMF$_{15}$-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3193.7	5051.3	6041.3	3264.6	4659.7	6181.1
A_E (kg [DM] kg^{-1} [N])	-	12.38	9.49	-	9.30	9.72
Urea-N (kg ha^{-1})	-	-	-	-	-	-
Yield (kg [DM] ha^{-1})	3193.7	4903.5	5647.5	3264.6	4906.7	5935.6
A_E (kg [DM] kg^{-1} [N])	-	11.40	8.18	-	10.95	8.90

The decrease in R_N between-years recorded in OMF-treated grass was from *c*.41% to 26% for OMF_{10} and from *c*.51% to *c*.25% for OMF_{15}. Therefore, it is reasonable to state that NUE, as determined by R_N, was significantly affected by the fertiliser application method, and that the surface-application of urea-containing fertilisers, under the prevailing experimental conditions, provided the opportunity for volatilisation of ammonia. The decrease observed in the index (R_N) was proportional to both the nitrogen application rate and the content of urea-N in the fertiliser. In the second year of the studies, the fertilisers were applied on 2nd June 2008 and although there are not records for temperature inside the glasshouse for that day, based on 2009's records, it is expected that inside-temperatures had been warm.

Kokkora (2008) based on Wild (1988) and Tisdale et al. (1999), also reported possible losses of ammonia-N in a study using similar environmental conditions and attributed to this effect the relatively low nitrogen recoveries of mineral nitrogen fertilisers. According to these authors, losses of nitrogen via volatilisation of ammonia can increase significantly when the fertiliser is surface-applied on a soil being in the proximity of field capacity and when high evaporation rates persists for a number of days; e.g. air temperatures above 20°C (Darwich, 1998). Such conditions existed in the glasshouse around the time the fertilisers were applied. Chambers and Dampney (2009) reported ammonia emission factors; i.e. $NH_3 - N$ loss as percentage of total nitrogen applied, from granular urea of 27% (range of 10% to 58%) for grassland soils which provides a good indication of the magnitude of this process.

On the other hand, the reduction in R_N recorded in biosolids-treated pots between 2007 and 2008 can be attributable to the need for the biosolids' granule to be in complete contact with the soil to favour its decomposition and the breaking-down of organic-N components which was not fully achieved when the material was applied on the surface. The estimation of NUE by means of the agronomic efficiency index (A_E) showed a similar pattern as that of R_N.

Overall, the sandy loam soil resulted in significantly higher (p=0.011) A_E values than the clay loam soil (mean values of 13.3% and 12.4% for the sandy loam and the clay loam soil respectively; $LSD_{[5\%\ level]}$ =0.64). In addition, there were significant differences in A_E with respect to the fertiliser type and the nitrogen application rate (p-values <0.001). The differences in A_E for the fertiliser type were encountered in both soil types (p=0.036). Overall, the interaction between the fertiliser type and the nitrogen application rate was found to be nonsignificant (p=0.077).

There were also significant differences in A_E with respect to the time which were recorded in both soil types (p-values <0.001); A_E decreased overtime from 17.6% in 2007 to 11.5% and 9.5% in 2008 and 2009 respectively which is also an indication of the effect that the surface-application of the fertilisers had upon the efficiency at which they were used up by the crop.

The largest reduction in this index (A_E) was observed in urea-treated pots from approximately 25.2% in year one to *c*.12.1% in year two and three (range 9.9% to 14.3%). The decrease in the index recorded for biosolids-treated pots was considerably smaller; i.e. from 11.8% in 2007 to 8.8% in the following two years with intermediate values for OMF_{10}- and OMF_{15}-treated pots; i.e. from 14.7% and 18.5% in year one to *c*.10.5% on average in the following two years respectively. As highlighted for R_N, the overall decrease in the A_E index was proportional to the nitrogen application rate and also to the concentration of urea-N in the fertiliser in both soil types.

The temperature and relative humidity recorded in 2009 for the day of the application of the fertilisers (30th May 2009) were 24.3°C (range of 17.2°C to 32.8°C) and 41.8% (range of 20.5% to 67.0%) respectively (Ghalamboran, 2011). These records also suggested favourable conditions for volatilisation of ammonia from urea-containing fertilisers applied on the soil surface. The relatively smaller reduction in A_E observed in biosolids-treated pots (and also R_N) indicated that the incorporation of the material in the soil had a significant effect in improving the efficiency at which nitrogen was used by the crop but it was less critical compared with the rest of the fertilisers tested. In a grassland situation, the type of fertilisers studied can only be incorporated during the seedbed preparation prior to establishment. Therefore, the spreading of OMF_{10} and OMF_{15} should ideally be conducted, and where feasible, considering the meteorological conditions for the day of the application; especially, temperature and rainfall. Darwich (1998) indicated that the occurrence of moderate rainfall; e.g. 20 mm, following the application of urea-containing fertilisers can significantly reduce losses of nitrogen by volatilisation as it is dissolved and incorporated into the soil.

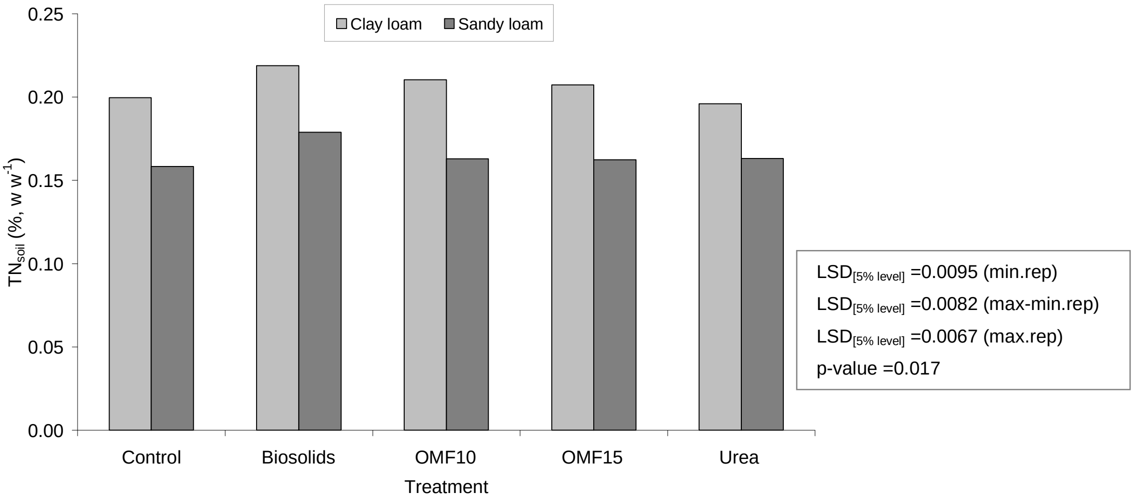
6.3.3 Soil analyses

i. Total soil nitrogen

The analyses of total nitrogen in soil (TN_{soil}) indicated that there were significant differences between the clay loam and the sandy loam soils (p<0.001). The former soil resulted in relatively higher TN_{soil} on average across all treatments (mean values of TN_{soil} of 0.207% and 0.166%, [w w^{-1}] for the clay loam and the sandy loam soils respectively).

There were also significant differences in TN_{soil} between the control and the treatments (p=0.001) and with respect to the fertiliser type used (p<0.001) which was observed in both soil types (p=0.017). Overall, the differences with respect to the nitrogen application rate were nonsignificant (p=0.458) but there was a significant effect of the interaction between the fertiliser type and the nitrogen application rate (p=0.02) on the TN_{soil} values encountered. In addition, significant changes (increase) in TN_{soil} were observed overtime (p<0.001) which were also encountered with respect to the fertiliser type used (p<0.001). On average, TN_{soil} increased at a rate of approximately 6% year on year across the whole experiment. At the end of the experiment, the pots amended with biosolids, OMF_{10} and OMF_{15} reached approximately the same level of TN_{soil} (values in the range of 0.198% to 0.215% [w w^{-1}]) which were significantly higher than that of urea (0.191% [w w^{-1}]) for an $LSD_{[5\% \text{ level}]}$ value of 0.008. The similarity in the levels of TN_{soil} recorded in the final year of the experiment, to certain extent, may help to explain the small variation in dry matter yield encountered in 2009 between the treatments since N-mineralisation from all pots would be approximately equivalent. However, this statement does not appear to be very conclusive since the C:N ratios encountered at the end of the experiment were found to be statistically higher (p<0.001) than those recorded in 2007 (mean values of C:N ratio were 11.46 and 11.76 at the start and at the end of the experiment respectively; $LSD_{[5\% \text{ level}]}$ =0.071). The statistical analysis also indicated that the changes in C:N ratios overtime were significantly different with respect to the soil type (p<0.001) and that a larger increase was recorded in the sandy loam (from 10.95 to 11.46) compared with clay loam soil (from 11.96 to 12.05). In addition, the differences in C:N were nonsignificant as a result of the fertiliser treatment (p=0.749), the nitrogen rate (p=0.302) and the interaction between the two factors (p=0.834). It can also be argued that the differences in C:N between the initial levels and those recorded at the end of the trial were very small and that the ratios remained well below the upper limit required for net mineralisation; i.e. 20-30:1 (Tisdale et al., 1990; Addiscott et al., 1991; Throe and Thompson, 1993; Darwich, 1998). Although the differences in C:N ratios mentioned above were significant, it is unlikely that the magnitude of these changes will have an effect in practice. Therefore, it is expected that mineralisation of organic-N would have progressed at approximately the same rate in all treatments which also helps to explain the similarities in the results corresponding to dry matter yield across the whole experiment in 2008 and 2009. The small differences in dry matter yield recorded on average for the two soil types in 2009 (**Section 6.3.1**) were also consistent with the C:N ratios of the soils in 2009; i.e. a significantly lower C:N ratio in the sandy loam compared with the clay loam soil provided the opportunity for larger supply of nitrogen to the crop which was reflected in the yields obtained.

The significant effect of the interaction between the fertiliser type and the nitrogen rate was mainly due to differences in TN_{soil} encountered between biosolids- and urea-treated pots, and in particular, when the pots were fertilised at the equivalent rate of 300 kg [N] ha^{-1} (mean values of TN_{soil} of 0.202% and 0.176% [w w^{-1}] for the pots amended with biosolids and urea respectively; $LSD_{[5\% \text{ level}]}$ =0.005). The pots treated with OMF_{10} and OMF_{15} resulted in intermediate levels of TN_{soil} ranging from 0.183% to 0.187% [w w^{-1}] for both nitrogen application rates. These values were not significantly different from each other for the same LSD value quoted above. As highlighted in **Section 6.3.1**, losses of nitrogen via volatilisation of ammonia were presumably important following the surface-application of urea-containing fertilisers in 2008 and 2009. This helps to explain the overall lower TN_{soil} values in these pots when compared with the pots that had been amended with biosolids. It also reinforces the hypothesis that the reduction in dry matter yield in urea-treated pots occurred as a result of low efficiency of the nitrogen applied in the form of urea associated with volatilisation of ammonia. The results of TN_{soil} are summarised in **Figure 6.14**.



$LSD_{[5\% \text{ level}]}$ =0.0095 (min.rep)
$LSD_{[5\% \text{ level}]}$ =0.0082 (max-min.rep)
$LSD_{[5\% \text{ level}]}$ =0.0067 (max.rep)
p-value =0.017

Figure 6.14: Mean TN_{soil} for the control pots and the treatments in the two soil types. The values shown in the graph correspond to the mean value for the two nitrogen application rates used (n=6 except controls n=3).

ii. Soil mineral nitrogen

Analyses of soil mineral nitrogen (SMN) were conducted at the same times as those of TN_{soil}. With the exception of the year of establishment, the values of SMN recorded in the analyses were consistently very low (≤2.40 and ≤1.60 mg [N] kg^{-1} for the clay loam and the sandy loam soils respectively).

Expressed in kg [N] ha^{-1}, these values represented a small amount of available nitrogen ($\leq$5.85 and $\leq$4.30 kg [N] ha^{-1} for the clay loam and the sandy loam soils respectively). On the contrary, the values of SMN encountered at the start of the experiment were considerably higher; i.e. 57.83 and 35.22 kg [N] ha^{-1} equivalent for the clay loam and the sandy loam soils respectively which, added to the nitrogen applied with the fertilisers, help to explain the significantly higher dry matter yields obtained in the first year of the experiment.

A possible reason for the overall low values of SMN obtained in the 2nd and 3rd years is with regards to the timing of sampling which were recorded on 1st June 2008 and 30th May 2009 respectively. At that time of the year, the grass was actively growing, as recorded by visual assessment, which provided an indication that nitrogen uptake was also high and therefore the values obtained in soil analyses were low. In 2007, the high values encountered respond to the disturbance of the soil following its collection from the field. The statistical analysis indicated that there were significant differences in SMN between the two soil types which were also observed overtime (p-values <0.001 respectively).

Overall, the differences recorded between the control and the treatments and with respect to the fertiliser type were found to be significant (p=0.098 and p=0.723 respectively). However, there was a significant effect of the nitrogen application rate (p=0.02) with the treatments receiving 300 kg [N] ha^{-1} yielding a significantly higher SMN values compared with the controls and those fertilised at 150 kg [N] ha^{-1}. It is important to emphasise that these differences were very small and almost negligible when converted to kg [N] ha^{-1} (mean values of 5.05, 5.18 and 5.41 mg [N] kg^{-1} for the controls, and the pots fertilised at 150 and 300 kg [N] ha^{-1} respectively; LSD values (5% level) of 0.31 -for comparisons between the control and the treatments- and 0.20 for comparisons between treatments).

iii. Soil extractable phosphorus

The initial values of soil extractable-P for the two soil types and their corresponding soil-P indexes at the start of the experiment were shown in **Table 6.2**. The statistical analyses were conducted for the data corresponding to the results expressed in both units mg [P] kg^{-1} and also in mg [P] l^{-1}. As for the field studies, the discussion focused on the results reported in mg [P] kg^{-1} but reference was made to mg [P] l^{-1} to aid in the analysis and interpretation of the soil-P index. The conversion from [w w^{-1}] to [w v^{-1}] was done by multiplying the value in mg kg^{-1} by its corresponding soil bulk density in the natural state (**Table 5.1**).

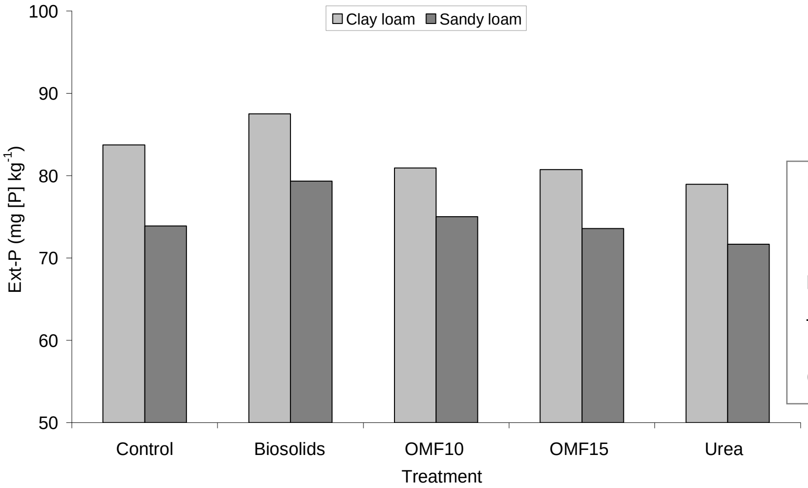
The differences in soil extractable-P encountered overall between the two soil types were found to be significant ($p<0.001$) when the results were expressed in mg [P] kg^{-1}; however, they were not when the values were compared in mg [P] l^{-1}; $p=0.894$). There was a small increase in soil extractable-P levels overtime, from an initial value of 77.65 to 79.34 mg [P] kg^{-1} at the end of the experiment (mean values across the whole experiment) which was found to be significant ($p=0.013$), and the effect was observed in both soil types ($p=0.008$). In addition, the statistical analysis showed that there were not significant differences between the control and the treatments ($p=0.738$) in none of the two soil types ($p=0.179$). However, there was a significant effect of the fertiliser type ($p<0.001$) with respect to the controls which was mainly due to the increase in soil extractable-P levels encountered in biosolids-treated pots and also to a small decrease recorded in urea-treated pots (mean values were 78.80, 83.41, and 75.30 mg [P] kg^{-1} for the controls, biosolids- and urea-treated pots respectively; $LSD_{[5\% \text{ level}]} = 2.34$).

The effect of the fertiliser type was also significant when factoring in the time ($p<0.001$); i.e. the changes recorded in biosolids- and urea-treated pots were significant with respect to the initial values recorded at the start of the experiment. These findings indicated that, in general, the continuous application of OMF_{10} and OMF_{15} did not induce a significant change in soil extractable-P levels compared with the untreated controls. These results are therefore consistent with the purpose of the proposed OMFs' formulations and their use implies an advantage with respect to the use of biosolids which were shown to induce a significant increase in soil extractable-P levels. Overall, however, the effects of the fertiliser rate and the interaction between the fertiliser type and the rate were nonsignificant ($p=0.201$ and $p=0.059$ respectively). The mean values of soil extractable-P encountered for each of the treatments at the end of the experiment are shown in **Figure 6.15** for both the clay loam and the sandy loam soils respectively.

The results shown in **Figure 6.15** were not significant ($p=0.699$) which indicated that the changes recorded in soil extractable-P levels compared with the controls in each soil types were of similar order of magnitude. When the values of soil extractable-P were expressed in mg l^{-1}, the statistical analysis indicated that biosolids increased soil-P index from 5 (initial level) to 6 at the end of the experiment in 2009 (mean values for the two soil types in biosolids-treated pots were 99.12 and 113.92 mg [P] l^{-1} in 2007 and 2009 respectively; $LSD_{[5\% \text{ level}]} = 3.48$). A small increase in soil extractable-P levels was also recorded for the control soils from 99.12 (initial level) to 102.01 mg [P] l^{-1} in 2009 but this change was found to be nonsignificant ($LSD_{[5\% \text{ level}]} = 4.92$).

This change, however, also suggested a change in soil-P index in the control soils from 5 to 6, since the upper limit for index 5 is 100 mg [P] l^{-1} (MAFF, 2000). Brady (1990) indicated that maximum phosphates availability to plants occurs at soil pH in the range of 6.0 to 7.0. In **Section 6.3.2-iv**, it was reported that the soil in the control pots showed a small increase in soil pH between the start and the end of the experiment (from 6.22 to 7.09 -clay loam- and from 6.91 to 7.12 -sandy loam-). Hence, the changes in soil-P levels in the controls cannot be clearly explained by the changes recorded in soil pH since the values encountered at the end of the experiment marginally exceeded the threshold of 7.0. However, they may be explained by reduced P-uptake by the crop in the control pots. In this respect, limited crop growth in control pots, due to the lack of nitrogen in the system, could have led to some accumulation of phosphorus in the soil overtime which was detected in the soil analyses.

It is important to highlight that the increase observed was only marginal compared with the initial levels reported for 2007. Analyses of total phosphorus in harvested plant material (TP_{plant}) conducted after the first cut in 2007 indicated that TP_{uptake} in the control pots was significantly lower ($p<0.001$) than the treated pots. There were also significant differences in TP_{uptake} between the fertiliser types and the nitrogen application rates used (p-values of 0.001).



$LSD_{[5\% \text{ level}]}$ =3.820 (min.rep)
$LSD_{[5\% \text{ level}]}$ =3.308 (max-min.rep)
$LSD_{[5\% \text{ level}]}$ =2.701 (max.rep)
p-value =0.699
Initial levels:
(Clay loam: 82.3 mg [P] kg^{-1})
(Sandy loam: 73.0 mg [P] kg^{-1})

Figure 6.15: Mean soil extractable-P (Olsen's-P) recorded for the control pots and the treatments at the end of the experiment in 2009 in the two soil types. The values shown in the graph correspond to the mean value for the two nitrogen application rates used (n=6 except controls n=3).

TP_{uptake} was increased with both the nitrogen application rate and with the concentration of readily available nitrogen in the fertiliser (mean values of TP_{uptake} for the two soil types were 0.89, 1.42, 1.687, 1.70 and 1.71 kg [P] ha^{-1} respectively for the controls, biosolids-, OMF_{10}-, OMF_{15}-, and urea-treated pots; $LSD_{[5\% \text{ level}]}$ =0.187 for control *vs*. treated, and 0.16 for comparisons between the treatments). Although these analyses were conducted for a single harvest event, they provided some indication of phosphorus uptake by the crop and its relationship with the fertiliser type used. The results of these analyses are presented in **Appendices A.6.8** and **A.6.9**.

The use of OMF_{10}, OMF_{15}, and urea did not induce significant changes in soil-P index with respect to the controls but they were all significantly different from the value encountered in biosolids-treated pots. The decrease in soil extractable-P observed in urea-treated pots was not sufficient to modify the index. These results are summarised in **Table 6.9**.

Table 6.9: Changes in soil-P index recorded between the start of the experiment in 2007 and the end of the trial in 2009 [$LSD_{[5\% \text{ level}}$ =4.92 (min.rep); 4.26 (max-min rep.); 3.48 (max. rep); (n=12; except controls and initial level n=6)].

Treatment	Ext-P (mg [P] l^{-1})	Soil-P index
Mean initial level (2007)	99.12	5
Mean level end experiment (2009)	-	-
▪ **Controls**	102.01	6
▪ **Biosolids**	113.92	6
▪ **OMF_{10}**	100.13	5
▪ **OMF_{15}**	97.97	5
▪ **Urea**	93.22	5

iv. Soil pH

The initial values of soil pH reported in **Table 6.2** at the start of the experiment were significantly different ($p<0.001$) between the two soil types, and the same was observed between both soils at the end of the experiment ($p<0.001$). When comparing soil pH values at the start and at the end of the experiment, there was an overall significant increase in soil pH after three years (from 6.56 to 7.12 – mean values across the whole experiment recorded in 2007 & 2009 respectively; $LSD_{[5\% \text{ level}]}$ =0.0201). This increase may be attributable to the deposition of Ca^{2+} and Mg^{2+} in the form of carbonates present in the irrigation water which would help explaining why soil pH increased in both the control and the treatments.

Despite the increases in soil pH recorded overall, there were not significant differences between the controls and the treatments ($p=0.583$), and the same was observed for comparisons between the fertiliser types used ($p=0.085$). However, there was a significant effect of the nitrogen application rate ($p<0.001$) on soil pH. The pots fertilised at 300 kg [N] ha^{-1} showed a significantly lower value (pH 6.82) than those that received 150 kg [N] ha^{-1} year on year (pH 6.87). This effect could be associated with larger removal of Ca^{2+} and Mg^{2+} with the harvested grass; although, this cannot be fully supported with the data available, and possibly with larger accumulation of SOM in the pots receiving the highest fertiliser rate (SOM =4.88% and 4.75% for the high and the low fertilisation treatments respectively; $p<0.001$). The effect of the rate on soil pH is, however, not very clear as the differences encountered were only marginal (mean values of 6.83, 6.87 and 6.82 for the controls and the treatments receiving 150 and 300 kg [N] ha^{-1} respectively; LSD$_{[5\% \text{ level}]}$ =0.022). The range of soil pH values encountered in both soil types were within the range (6.0 to 7.0) required for perennial rye grass for optimum growth (Hall, 1992).

v. Soil organic matter

Soil organic matter (SOM) increased significantly at the end of the three year's trial from 4.38% to 5.19% on average across the whole experiment. The overall increase in SOM occurred in both soil types for which the differences observed between the two soils were nonsignificant for the interaction between the soils and the time ($p=0.419$). The statistical analysis also indicated a significant increase in SOM for the treatments with respect to the controls from 4.60% to 4.81% (LSD$_{[5\% \text{ level}]}$ =0.095). In addition, significant differences in SOM levels were found overall for the control and the treatments with respect to the fertiliser type and also the nitrogen application rate (p-values <0.001) whereas the interaction between the two factors showed a nonsignificant effect ($p=0.293$). SOM increased by approximately 3.2% and 5.9% for the treatments fertilised with 150 and 300 kg [N] ha^{-1} respectively at the end of the three years' trial compared with the initial levels recorded in 2007. The largest increase in SOM was recorded in the pots treated with biosolids (by *c*.7%) compared with the controls whereas for urea and the two OMF, SOM levels were approximately between 2.3% to 4.75% higher than the controls respectively.

When analysing the data corresponding to each of the soil types individually, all fertilisers induced similar changes (increases) in SOM compared to the controls ($p=0.912$). The effect of the fertilisers within each soil type followed the same overall trend as biosolids which produced, consistently, the largest increase in SOM levels. The effects of the fertiliser type on SOM are shown in **Figure 6.16** for the clay loam and the sandy loam soils respectively.

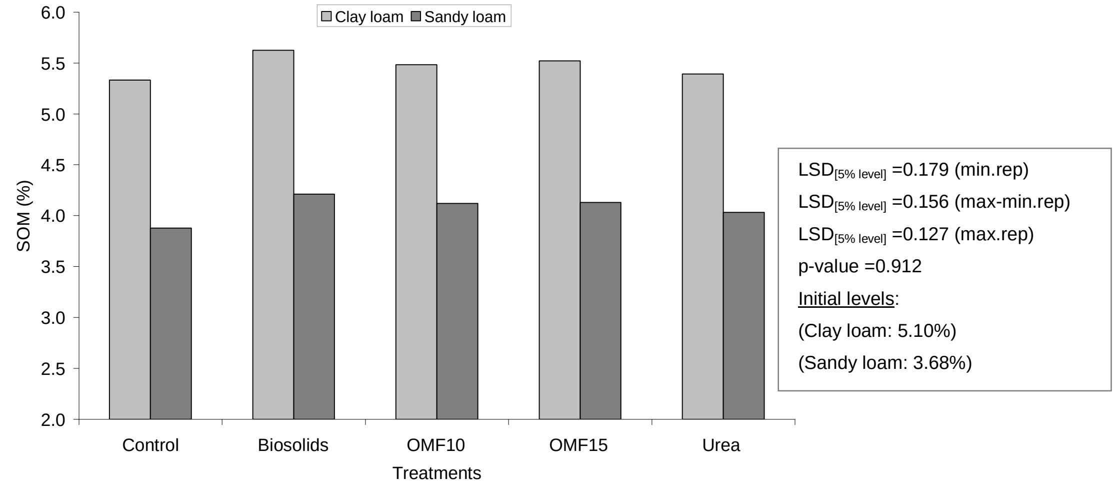


Figure 6.16: Soil organic matter recorded for the control pots and the treatments at the end of the experiment in 2009 in the two soil types used (n=6; except controls n=3).

6.4 Overall discussion

The results presented in this chapter highlighted the numerous factors affecting the response of grass to the application of nitrogen fertilisers with particular regards to OMF-N. Response curves enable the derivation of the economic optimum of applied nutrients on the basis of the price of the fertiliser and the crop (Melgar and Muñoz, 2008). It is argued, however, that this traditional approach does not meet the requirements of the diversity of grassland-based systems that exist in milk and meat production where the primary objective is to provide sufficient grass-energy to be able to meet the demand of the production system (Fisher and Jewkes, 2009). In this respect, a more comprehensive approach which also takes account of the energy and protein requirements of the system, including that provided by non-grass crops grown on the farm, has been recently developed by Fisher and Jewkes (2009). In agreement with these authors and with the need to account for the energy requirements of the production system, it is believed that the results coming from the study of the responses of rye grass to the application of organomineral fertilisers will provide a valuable dataset to aid in the development of strategies to optimise grass production (both dry matter yield and energy output) and also the use of OMF-N on-farm.

It has been indicated that grass crops typically respond linearly to the application of nitrogen to rates within the range of 0 to 300 kg [N] ha^{-1} per year (Sparrow, 1979; Morrison et al., 1980; Fisher and Jewkes, 2009) but this is very dependent on the characteristics of the site and the management of the grass sward (Fisher and Jewkes, 2009).

The responses of grass to OMF-N reported for the glasshouse studies were in agreement with some of the previous works on the subject. In most circumstances, the grass yield data presented did not permit the use of quadratic functions to describe its relationship with increasing nitrogen application rates. For the range of nitrogen rates investigated, these relationships were better explained by linear functions and it was also shown that the R^2 values indicated acceptable fits of the linear models ($R^2 \geq 0.75$).

Annual dry matter yield varied both within- and between-years and also between-treatments. In general, the use of biosolids resulted in relatively stable levels of biomass production throughout the experiment (mean value of 5476 kg [DM] ha^{-1} – range of 5178 to 5637 kg [DM] ha^{-1}). For OMF_{10}, OMF_{15} and urea mean annual levels of production of dry matter in the two soil types were 5910 kg [DM] ha^{-1} (range of 5261 to 6375 kg [DM] ha^{-1}), 6239 kg [DM] ha^{-1} (range of 5483 to 7149 kg [DM] ha^{-1}), and 6877 kg [DM] ha^{-1} (range of 5348 to 8700 kg [DM] ha^{-1}) respectively. The figures shown above represent mean increases in annual dry matter yield with the use of OMF_{10} and OMF_{15} of approximately 8% and 14% respectively compared with biosolids for the three years period (2007-2009).

It was found that in the first year of the experiment, the increments in dry matter yield, for every additional unit of nitrogen applied, were related with the concentration of readily available nitrogen in the fertiliser and that the crop showed higher responses to the application of OMF_{10}, OMF_{15}, and urea compared with biosolids. In 2007, the increments in dry matter yield for OMF_{10}, OMF_{15}, and urea were in the range of 14 to 26 kg [DM] ha^{-1} per kg of additional N. These were found to be consistent with the range of responses reported in the literature; typically, 15 to 30 kg [DM] ha^{-1} per kg of additional N (Morrison et al., 1980; MAFF, 2000). The responses to the application of biosolids in the first year were lower compared with OMF_{10}, OMF_{15} and urea (range of 10 to 12 kg [DM] ha^{-1} per kg of additional N). The larger soil nitrogen supply in the clay loam compared with the sandy loam soil in 2007 (*c*.+25 kg [N] ha^{-1}) also helps to explain the overall higher increments in dry matter yield achieved in the latter soil for each additional unit of nitrogen applied. In the following two years of the experiment, the slope of the regression lines fitted to the data; i.e. dry matter yield *vs*. nitrogen application rate, indicated that the expected increments in dry matter yield for every additional unit of nitrogen applied were of similar order of magnitude for all treatments, ranging between 6.5 to 11.7 kg [DM] ha^{-1} per kg of additional N.

These were found to be approximately 50% lower than the mean values of response reported by Morrison et al. (1980) for 21 experimental sites across England and Wales and fertilised at a rate of 300 kg [N] ha^{-1}. This overall decrease in the responses in 2008 and 2009 may be attributed to the method of fertiliser application, and possibly, to nitrogen losses by means of volatilisation of ammonia (except for biosolids). The high response of the grass to the application of urea in 2008 at the rate of 150 kg [N] ha^{-1} on the clay loam soil (mean value of 6814.8 kg [DM] ha^{-1}; *SD* =624.08) could not be clearly interpreted. However, it is worth noting the large variability observed in the data within that treatment in 2008 (values obtained for each of the three samples corresponding to that treatment were plotted in **Figure 6.6**).

The optimum nitrogen application rate could not be determined under the prevailing experimental conditions due to the linearity of the responses of dry matter yield obtained. Therefore, a recommendation may be made to investigate the responses at larger nitrogen application rates and using smaller nitrogen rates-increments than those reported in this study. There is also need to investigate the response of rye grass to OMF under grazing regimes which could not be examined in the current work, though; they may be of importance for the operating area of United Utilities plc. **Table 6.10** shows a summary of dry matter yields obtained in the glasshouse studies, relative to biosolids. It can be seen that yields tended to match that of biosolids overtime.

Table 6.10: Differential (mean) dry matter yield ($\Delta\overline{Y}$; kg [DM] ha^{-1}) and dry matter yield relative to biosolids (%$\overline{Y}$ of biosolids-treated plots) for the rye grass grown in the glasshouse between 2007 and 2009 [Mean values across the whole experiment].

Treatment/	Biosolids		OMF_{10}		OMF_{15}		Urea	
Year	$\overline{Y}$	%	$\Delta\overline{Y}$	%	$\Delta\overline{Y}$	%	$\Delta\overline{Y}$	%
2007	5613	100	693	112.3	1536	127.4	3087	155.0
2008	5637	100	456	108.1	448	107.9	946	116.8
2009	5278	100	-17	99.7	205	103.9	70	101.3

An important feature in the response of the grass to the nitrogen applied was the parallelism of the regression lines in 2008 and 2009; this was not observed in the year of establishment. These results could be partially attributable to the particular conditions recorded inside the glasshouse; most importantly, temperature and relative humidity, around the date the fertilisers were applied both years. It is also important to note that in 2008 and 2009, the fertilisers were applied later than in 2007 (see **Appendix A.6.6**).

The date of the fertiliser application (in relation to the maximum growth rate of the grass) could also be responsible for the relatively lower yield responses of the grass to the fertiliser applied and the nitrogen use efficiency. Anslow and Green (1967) demonstrated that, for perennial rye grass, the maximum rate of herbage production (kg [DM] ha^{-1} day^{-1}) typically occurs within the first two weeks of May. There is also a second but significantly smaller peak of growth around July which is followed by a progressive decline in the production of DM towards the autumn. In both years, 2008 and 2009, the first and most important peak of growth was missed by the late fertiliser application which could explain the lower responses obtained those years. However, it is important to highlight that there was a need to quantify the yield of the grass up to the first cut (conducted prior to the date of the fertiliser application) in order to determine possible residual effects of the fertilisers applied in previous years. This also needed to be assessed during the maximum growth period to be able to detect differential effects in dry matter yield as a result of the fertiliser type.

Watson (1987) based upon the work of Van Burg et al. (1982) highlighted that a minimum of 5 mm of rainfall is needed for surface-applied urea in order to significantly reduce N-losses by volatilisation of ammonia following its application. Watson (1987) also found that the largest differences in dry matter yield of rye grass grown in pots and treated with urea and ammonium nitrate were found when the soils were at field capacity at the time of fertiliser application. The author mentioned above attributed the lower yield in urea-treated pots to volatilisation of ammonia. Work undertaken by Campos-Bernardi et al. (2010) indicated that urea applied at 50 kg [N] ha^{-1} to pots-grown rye grass resulted in losses equivalent to *c*.21% and *c*.11% of the total nitrogen applied for surface-applied and soil-incorporated urea respectively. The work of Cookson (1999) highlighted that a significant relationship was found between increasing nitrogen application rates (range 0-350 kg [N] ha^{-1}) and volatilisation of ammonia in urea-fertilised rye grass crops. In addition, Ismail et al. (1991) quoted the work of Ernst and Massey (1960) who demonstrated that ammonia loss from a silty loam soil (pH 6) accounted for 15-23% of the total nitrogen applied for air temperatures in the range of 24 to 32°C, and Kumar and Wagenet (1984) reported a linear increase in urease activity for temperatures ranging from 5 to 35°C. As highlighted earlier, the mean temperature recorded on the date of the application of the fertilisers in 2009 was 24.3°C which support the possibility of some volatilisation of ammonia, the consequent reduction in dry matter yield, and the parallelism in the response curves (assuming also a similar effect in 2008).

By contrast, it was suggested that the overall high temperatures (and soil moisture conditions) recorded in the glasshouse during the summer time could have benefited the mineralisation of organic biosolids-N, and as a result, dry matter yield in biosolids-treated pots was sustained over the years at approximately the same level. Possibly, this process also occurred in OMF-treated plots but, comparatively, to a lesser extent due to the smaller proportion of organic-N in their composition. For this reason, the differences in dry matter yield encountered in 2008 and 2009 between the treatments, although significant, were smaller compared with the first year. It is important to highlight that the period allowed between the first and the third cuts in 2007 was 20 and 25 days shorter respectively than that of the following two years. Hence, mineralisation of organic-N from the biosolids and OMF progressed for longer in years two and three of the experiment which contributed to sustain dry matter yield in those pots compared with urea; especially in the third cut. Therefore, it can be stated that the experimental conditions in the glasshouse significantly influenced the response of the grass to the application fertilisers. Consequently the response curves, especially in years two and three of the experiment, may not be considered as characteristics and they should be treated with caution when trying to predict a typical grass yield response from the fertilisers tested.

Nitrogen uptake was significantly increased with the nitrogen application rate and linear relationships were established between the two parameters. Regression analyses were undertaken to determine the relationship between TN_{uptake} and nitrogen application rate. The data obtained for 2007 showed that the increments in TN_{uptake} tended to be higher for the products containing a larger concentration of readily available nitrogen in its composition. These were 0.28, 0.41, 0.48 and 0.82 kg [TN_{uptake}] ha^{-1} per kg of additional N for biosolids, OMF_{10}, OMF_{15}, and urea respectively. However, in 2008, the slope of the regression lines fitted to the TN_{uptake} data indicated similar increments for all treatments, ranging from 0.20 to 0.24 kg [TN_{uptake}] ha^{-1} per kg of additional N. In both years, these relationships were consistent with those encountered between dry matter yield and nitrogen application rate.

In general, the increase in the nitrogen application rate from 150 to 300 kg [N] ha^{-1} significantly increased TN_{plant} (by *c*.8% on average across the whole experiment) which was consistent with earlier studies (Aavola and Kärner, 2008). The effects of the reduction in the nitrogen fertilisation levels on the productivity and the quality of grass crops are well understood (Delagarde et al., 1997; Binnie et al., 2001). Low nitrogen supply to the grass crop compromises growth rate, tiller density and biomass production (Wilman, 1980; Delagarde et al., 1997), and reduces the nitrogen concentration in plant (Delagarde et al., 1997).

In particular, low nitrogen contents in grass crops are associated with reduced protein supply to the cattle which restricts milk yield affecting individual animal's performance (Delaby et al., 1996). Based on the work of Van Vuuren (1990) and later Aavola and Kärner (2008), high-producing dairy cows require nitrogen contents in grass in the range of 2.2% to 2.7% [N] w w^{-1}. Wilkins et al. (2000) indicated a lower threshold of 20 g [N] kg^{-1} required by productive-grazing animals. The work of Wilkins et al. (2000) also highlighted a large seasonal variation in nitrogen content in herbage which was regardless of the variety. The same work indicated that N content in leaf declined below the critical level in May when the leaf content of the herbage was lower. The results of the analyses of TN_{plant} indicated that the grass fertilised with OMF_{10}, OMF_{15} and urea at the equivalent rate of 300 kg [N] ha^{-1} reached such levels of nitrogen content in plant on both soil types (range of 2.18% to 2.74% [N] w w^{-1}) but only in the first year of the experiment.

Overall, the values of TN_{plant} were lower in the second year by approximately 14% – on average across the whole experiment. This was more evident in OMF- and urea-treated pots compared with the pots amended with biosolids (range of 1.90% to 2.05% [N] w w^{-1}); possibly, in response to a dilution effect with increased dry matter accumulation. In 2007, despite the large level of dry matter yield obtained, the dilution effect was probably offset by the SMN levels recorded prior to the start of the experiment. This effect has been widely investigated and it is related with the decline, overtime, in the nitrogen requirement of the grass crop per unit of incremental dry matter (Caloin and Yu, 1984; Greenwood et al., 1991; Marino et al., 2004). In this respect, Aavola and Kärner (2008) highlighted that higher nitrogen contents in harvested plant material may be obtained by means of frequent defoliation. In the first year of the study, there was a significant interaction between the soil type, the fertiliser type and the nitrogen rate with respect to total nitrogen uptake by the crop. TN_{uptake} was significantly increased with the nitrogen application rate used and the concentration of readily available nitrogen in the fertiliser, and the total uptake by the crop was greater in the clay loam soil. Mean TN_{uptake} (for the two soil types and nitrogen rates used) accounted for 122 kg [N] ha^{-1} (range of 97 to 156 kg [N] ha^{-1}), 148.4 kg [N] ha^{-1} (range of 104 to 186 kg [N] ha^{-1}), 169.7 kg [N] ha^{-1} (range of 115 to 212 kg [N] ha^{-1}), and 232.1 kg [N] ha^{-1} (range of 144 to 331 kg [N] ha^{-1}) for biosolids-, OMF_{10}-, OMF_{15}- and urea treated-pots respectively. TN_{uptake} in the unfertilised control-pots was 57 kg [N] ha^{-1} (range of 41 to 72 kg [N] ha^{-1}). A similar effect was observed in the second year of the study but the differences encountered were, overall, nonsignificant for the interaction between the soils, the fertiliser type and the nitrogen application rate.

The values of TN_{uptake} recorded in 2008 for biosolids, OMF_{10}, OMF_{15} and urea were, respectively, 6%, 19%, 38% and 73% lower than those recorded in 2007. Estimates of nitrogen use efficiency (NUE) by means of apparent recovery (R_N) and agronomic efficiency (A_E) of applied nitrogen also indicated large differences between-years with an overall decrease in all treatments in 2008. In 2007, and on average across the whole experiment, values of R_N were found to be 29% for biosolids, 41% for OMF_{10}, 51% for OMF_{15}, and 75% for urea. In 2008, these values decreased to 20% and to 31% for biosolids and urea respectively whereas for OMF_{10} and OMF_{15} R_N was reduced to *c*.25%. These differences in R_N observed between the fertilisers were found to be significant. Although the differences observed overall as a result of the nitrogen application rate were nonsignificant, a relatively lower R_N value was obtained when nitrogen was applied at 300 kg [N] ha^{-1}; i.e. 36.5% versus 38% recovery at 150 kg [N] ha^{-1}. There was also a significant effect of the soil; the estimated recovery in the sandy loam soil was on average 38.7% whereas for the clay loam soil it was 35.5%. The same was observed for NUE as estimated by A_E (mean values were 13.3 and 12.4 (kg [DM] kg^{-1} [N]) for the sandy loam and the clay loam soils respectively). A_E decreased also in 2008 and 2009 compared with 2007 and it was suggested for both indexes that this was associated with the surface-application of the fertilisers and the content of urea-N in the fertilisers, and the timing of fertiliser application (late N-application) in relation to the maximum rate of growth of the grass (Anslow and Green, 1967). This latter statement is also true for the general decline observed in R_N overtime. Based on these results, it was also suggested that the application of OMF to grass crops, where feasible, should be conducted with favourable weather conditions to minimise losses of nitrogen by volatilisation. Cookson (1999) reported values of recovery in the range of 18% to 43% for lysimeters-grown rye grass maintained between 70% and 90% of field capacity (sandy loam soil) and fertilised at a similar range of nitrogen application rates (0-350 kg [N] ha^{-1}). Morrison et al. (1980) found recoveries in rye grass fertilised at 150 and 300 kg [N] ha^{-1} of *c*.65% and *c*.70% respectively; the latter nitrogen rate had recoveries in the range of 45% to 87%, but it was reported that a larger variability was found for recoveries at the lower nitrogen rate.

Morrison et al. (1980) quoted earlier works undertaken by Whitehead (1970) and Whitehead et al. (1978) that found recoveries of similar order of magnitude to those indicated above. Values of total nitrogen yield in herbage of approximately 210 kg [N] ha^{-1} were reported by Wilkins et al. (2000) for rye grass (*var.* AberElan) fertilised at 300 kg [N] ha^{-1}. In general, the values of nitrogen recovery encountered in the first year of the studies in the glasshouse appeared to be within the range reported in the literature; whereas the values for 2008 were substantially lower.

The results obtained by Williams et al. (2000), however, appeared to be in closer agreement to those showed earlier for 2008. Their results indicated that at the time of harvest, a perennial rye grass-seed crop fertilised with 180 kg [urea-N] ha^{-1} was found to have 9% of the ^{15}N applied in the seeds plus 29% in the straw and there were 19% and 39% of the nitrogen in the roots and SOM respectively.

The soil analyses indicated that, after three years, there was a significant increase in the level of TN$_{soil}$, SOM, and soil extractable-P. At the end of the experiment, biosolids-, OMF$_{10}$- and OMF$_{15}$-amended pots resulted in approximately the same level of TN$_{soil}$ with values in the range of 0.198% to 0.215% (w w^{-1}). By contrast, TN$_{soil}$ in urea-treated pots was found to be significantly lower (0.191% [w w^{-1}]) than the other fertiliser treatments. There was also a build up of TN$_{soil}$ levels overtime which occurred at a rate of *c*.6% year on year on average for all treatments in both soils types. The rate of build up in TN$_{soil}$ was marginally greater in the sandy loam (from 0.145% to 0.181% [w w^{-1}]) compared with the clay loam soil (from 0.192% to 0.220% [w w^{-1}]). It was expected therefore that this effect had contributed to narrow the differences observed initially in dry matter yield between the two soil types through enhanced release of SMN in the sandy loam compared with the clay loam soil. To some extent, crops cultivated on coarser textured soils usually demand for larger amounts of N-fertiliser as supply of mineral nitrogen can be limited by relatively lower SOM contents in these soils (Cordovil et al., 2006). In this respect, Morrison et al. (1980) highlighted that the amount of nitrogen mineralised from the soil is expected to be larger in older grass crops; and that, it could contribute significantly to the nitrogen supply of grass (referring to a field situation). This may be a possible explanation to the similarities in the responses in the last two years as TN$_{soil}$ and SOM built up overtime but comparatively at a larger rate in the sandy loam soil. This statement however cannot be supported with the data available as the values of SMN encountered were very small, except for the year of establishment.

The mean values of SMN were ≤2.24 mg [N] kg^{-1} (≤5.5 kg [N] ha^{-1}) and ≤1.56 mg [N] kg^{-1} (≤4.2 kg [N] ha^{-1}) for the clay loam and the sandy loam soils respectively in all sampling events conducted in 2008 and 2009. These low values could not be clearly interpreted; however, they might be associated with large rates of nitrogen uptakes at the time of sampling thereby reducing the amount of SMN detected in the analyses. Nutrients' availability can be indirectly inferred by measuring plant uptake which is a function of the availability of soil nutrients and the crop's growth rate (O'Brien, 1998; Côrrea, 2004) and the concentration of nutrients in plant can provide an indication of the nutrient's supply (Havilah et al., 1996).

The data presented in **Chapter 5** showed that, during the 90 days incubation period, the majority of the nitrogen released from both urea and OMF_{15} occurred within the first 30 days following soil application. Hence, SMN is expected to be greater during this period and it was shown that TN_{plant} was greater in the first cut following fertiliser application. Subsequently, as smaller amounts of nitrogen are released overtime, these are immediately taken up by the crop thereby lowering SMN levels in the soil which may explain the low values encountered and also their consistency with the timing of soil sampling. The soil samples taken in 2008 (both at the beginning and the end of the growing season) were extracted immediately after but the extracts were maintained in the fridge for a long period of time which could have resulted in some degradation of SMN while in storage. This is though not conclusive as low values were also reported for 2009 in both sampling events. Soil sampling for determination of SMN at shorter time intervals would have been advantageous. Smith and Tibbett (2004) provided evidence that supports the hypothesis that *Lolium perenne* preferentially uptakes $NH_4^+ - N$ over $NO_3^- - N$. Based on this work, SMN's data was examined for these two nitrogen species and it was found that both produced values of similar order of magnitude in all sampling events. Hence, the low SMN values encountered could not be attributed to this effect. SOM levels were significantly increased at the end of the three years' trial (by *c*.18% on average). These were observed in both soil types although the differences between the soils encountered at the end of the experiment were approximately equivalents to those recorded initially. Overall, there was a significant effect of the fertiliser type in increasing SOM levels. In general, SOM was increased to a greater extent in the pots treated with biosolids (from 4.61% to 4.92%) followed by those amended with OMF and urea (mean values of 4.81% and 4.71% respectively). This was in close agreement with Diacono and Montemurro (2010) who demonstrated that the continuous application of organic amendments to the soil significantly improved the overall fertility of the soil in comparison with mineral fertilisers.

The changes in soil pH between the control and the treatments were not significant despite the overall increase in the values recorded between the start and the end of the experiment; i.e. from 6.22 to 6.99 in the clay loam and from 6.91 to 7.26 in the sandy loam soil. It was suggested that this could be due to deposition of Ca^{2+} and Mg^{2+} from the irrigation water but the effect should be investigated. Interestingly, the pots that received 300 kg [N] ha^{-1} per year showed a significantly lower soil pH value than those at 150 kg [N] ha^{-1} (pH 6.82 and 6.87 respectively).

These differences were marginal but appeared to be statistically different and possibly linked to more accumulation of SOM and greater removal of Ca^{2+} and Mg^{2+} from the pots with the higher fertilisation regime (but this latter effect cannot be fully supported with the data available).

The analyses of soil extractable-P indicated that the use of OMF_{10} and OMF_{15} did not induce a change in soil-P index compared with the values recorded at the start of the experiment (soil-P index 5). For the pots fertilised with urea, soil-P index did not change but there was a statistically significant decrease in the soil extractable-P level after three years of continuous application of urea (from 99.12 to 93.22 mg [P] l^{-1}). For the pots treated with biosolids, soil-P index increased from 5 to 6 at the end of the experiment (mean value for biosolids-treated pots of 113.92 mg [P] l^{-1}). This may be attributable to the relatively low N:P ratio of biosolids as determined for the various batches produced between 2007 and 2009 (N:P ratios in the range of 0.60 to 0.74). Interestingly, there was an increase in soil-P levels in the control pots from 99.12 to 102.01 mg [P] l^{-1} which induced a change in the index from 5 to 6. This increase was marginal and it might have occurred as a result of reduced P-uptake in the controls pots. Analyses of TP_{plant}, and subsequent determination of TP_{uptake} conducted for the first harvest of grass in 2007, appeared to indicate that this was the case. However, these findings need investigating and the data should be treated with caution as the results reported corresponded to analyses conducted after a single sampling event; i.e. first harvest of grass conducted in 2007.

The reduction in the levels of soil extractable-P in urea-treated pots also provided an indication of the rate of decline in soil-P levels with not addition of P-fertiliser. In this respect, Johnston et al. (2001a) highlighted that prolonged avoidance of P- and K-fertilisation should not affect crop yield negatively unless soil-P and -K levels are low. The authors also indicated that evidence provided by long term experiments at Rothamsted showed that continuous omission of P- and -K application is likely to result in loss of crop yield once soil-P and -K reserves have decreased below a critical level (e.g. the ‘target indexes’ as specified in MAFF, 2000) in accordance with the soil and crop management systems. At low (available) P- and -K status, nitrogen use efficiency in grass crops is significantly affected which are both economically and environmentally unwanted (Johnston et al., 2001a; Johnston and Poulton, 2009).

The increase in soil extractable-P observed in biosolids-treated pots indicates the need to monitor soil-P status in soils receiving biosolids routinely, especially if the soil has already a satisfactory P-level. Generally, the build up of soil-P can increase the concentrations of both dissolved and particulate-P in runoff (Withers and Flynn, 2007).

The same work suggested that in order to reduce the risk of P-transfer from soil to watercourses, biosolids may be applied up to an index 4 on medium to heavy-textured soils without causing significant losses of P through leaching and runoff. It was also reported that the risk of P-transfer from soil to water increases rapidly when soil-P approaches a critical value of 20% saturation.

6.5 Conclusions

The main conclusions coming from **Chapter 6** are summarised below:

- The response of the grass to the application of biosolids, OMF_{10}, OMF_{15} and urea was found to be linear in the range of nitrogen rates investigated (0-300 kg N ha^{-1}).
- The differences in dry matter yield observed between the fertilisers became progressively smaller overtime. In 2007, mean dry matter yields, relative to that of biosolids (i.e. 100%), were 113.5%, 127.4%, and 155% for OMF_{10}, OMF_{15} and urea respectively; these were found to be significant. In 2008 and 2009, relative dry matter yields (to biosolids-treated soil) were 101.6% and 108.1% (OMF_{10}), 105.9% and 107.9% (OMF_{15}), and 103.3% and 116.8% (urea) respectively. These differences were significant in 2008 but they were not in 2009.
- The overall reduction in the performance of OMF_{10}, OMF_{15} and urea could be related to the method of fertiliser application (surface-applied), possible losses of nitrogen by volatilisation of ammonia and enhanced nitrogen mineralisation and uptake in biosolids-treated pots under the experimental conditions of the glasshouse, and the timing of fertiliser application in relation to the maximum growth rate of the grass (late N application).
- Similarly, the differences in TN_{uptake} between the fertilisers were greater in the first year compared with 2008 and this was shown by the parallelism of the regression analyses conducted. TN_{uptake} was increased with the nitrogen application rate. Both OMF showed almost identical values of nitrogen uptake in 2008 (between 122 and 125 kg [N] ha^{-1}; whereas for urea and biosolids total nitrogen uptake was 134 and 115 kg [N] ha^{-1} respectively).
- Overall, apparent nitrogen recovery was related with the concentration of readily available nitrogen in the fertiliser applied with both urea and OMF showing consistently larger R_N than biosolids. There were also significant differences in apparent nitrogen recovery between-years but for biosolids it remained relatively more stable (*c*.19% to 29%) than the other treatments (*c*.26% to 75%).

Hence, effect of the method for fertiliser application in year 2 of the experiment did not appear to have affected biosolids-N uptake and nitrogen use efficiency to the same extent as the other fertiliser materials.

- Similar observations as above can be made for A_E with respect to the fertiliser type with biosolids showing more stability in the index between-years, whereas for OMF (both) and urea, the index declined to 50% or more compared with the value encountered in the first year.
- TN_{soil}: the build up in the soil was found to be related to the concentration of organic-N in the fertiliser (biosolids > OMF > urea). This effect and the recorded increase in SOM, help to support the fact that dry matter yield (and the parameters investigated) was more sustained in biosolids-treated pots compared with the other treatments. SMN was found to be very low in all sampling events, possibly due to the timing of sampling in relation to crop growth, and also frequency of sampling.
- The application of OMF to the soil in the pots did not induce a significant change in soil extractable-P whereas in urea-treated pots, it decreased significantly while it showed a significant increase in biosolids-treated pots.
- In addition, both the control soil and the soil amended with biosolids, soil-P index changed (+1 level); whereas the changes recorded in urea-treated pots were not sufficient to modify the index despite the significant decrease recorded in soil-P levels. In OMF-treated soils, the index remained close to constant overtime; hence, supporting the purpose of the formulations.

CHAPTER 7

FIELD STUDIES

7 FIELD STUDIES

7.1 Introduction

Field experiments have long been used in agricultural, ecological and environmental research (e.g. Lawes and Gilbert, 1880; Johnston and Wedderburn, 1974; Johnston, 1975; Campbell, 1987; Johnston, 1987; Leigh and Johnston, 1994; Johnston and Powlson, 1994; Johnston, 1997). Specifically for grassland-research conducted on experimental plots, Fisher and Jewkes (2009) quoted the work of Morrison et al. (1980), Doyle and Elliot (1983), Large et al. (1983), Wilkins et al. (1984), Baker (1986), and Morrison (1987) upon which nitrogen recommendations for grass are currently based. Johnston (1997) acknowledged that the value of well designed and executed field experiments increases with time despite that the length of the experiments makes them inevitably more costly. The cost effectiveness of long-term experiments may be increased when numerous objectives are pursued and also when experiments are conducted on well typified sites which makes it possible to extrapolate the results to wider situations (Johnston, 1997).

The field studies conducted as part of this research aim to generate valuable information to farmers concerning the use of organomineral fertilisers and based on sound scientific facts. Extrapolation of the data coming from this work may be possible by bringing together the various experimental scales used in this research as described earlier in **Chapter 1.** The time scale allocated to this work helped to provide sufficient technical evidence to allow a realistic assessment of the effects of the use of organomineral fertilisers on soil fertility and crops productivity.

This chapter focuses upon the crop responses to applied fertilisers and the changes occurred in the soil nutrient status as a result of the continuous use of organomineral fertilisers. The experimental field work was a key component of this research and contributed to the understanding of nutrients management and dynamics in relation to the use of organomineral fertilisers in crop production. The findings coming from the field studies will lead to the development of practical recommendations concerning OMF application in winter wheat and rye grass. They will also provide the dataset needed to determine the economic benefits associated with their use in agricultural production which will be addressed later in **Chapter 8**.

The objectives of the field studies are summarised below:

- To determine the responses of winter wheat (*Triticum aestivum L.*) and rye grass (*Lolium perenne L.*) to the application of organomineral fertilisers in comparison with urea and biosolids granules,
- To generate technical data to be able to determine the optimum nitrogen application rate for the crops and the fertiliser types mentioned above,
- To determine the effects of continuous application of organomineral fertilisers on the fertility status of the soil with emphasis on nitrogen and phosphorus.

7.2 Materials and methods

7.2.1 Description of the experimental sites

The experiments were conducted in Avenue and Chippies Fields at the College Farm at Silsoe, on sandy loam soils classified as Cottenham series (King, 1969; Krajčo, 2007). Both soils are free draining; the site slopes gently in a west-easterly direction in Avenue Field and in an east-north westerly direction in Chippies Field where the soil becomes heavier. The soil in Chippies Field has a relatively coarser texture than that of Avenue Field. Smith and Trafford (1976) reported that the climatic conditions for Area 28 which includes the western part of East Anglia (comprising most of Cambridgeshire and Bedfordshire) is characterised by a mean annual rainfall of 574 mm (564.5 mm for the period 2006-09; Met Office, 2010). A mean excess winter rain of 130 mm is also recorded which allows the soil to return to field capacity around December 10th but not earlier than November 28th. The end of field capacity occurs around March 27th but usually not later than April 19th. Mean soil moisture deficits of up to 85 mm and 103 mm have been reported (Smith and Trafford, 1976) for the end of June and the end of July respectively which coincide with flowering and grain filling stages in winter cereal crops.

Rainfall and temperature data (Met Office, 2010) are reported in **Appendix A.7.1** for the period 2005-10. The fields had been under arable rotation prior to the start of the experiments. **Table 7.1** shows the crop sequence, nitrogen fertilisation levels and mean grain yields obtained for commercial crops sown in both fields; this provides a valuable reference for comparison of experimental data against that from standard farm practices. For Chippies Field, the crop sequence matched that of the commercial field during the years the experiment was conducted whereas for Avenue Field, after the second wheat (crop season of 2007-08), rye grass was established at the experimental site and it remained under grass for the following two years.

It is acknowledged that this crop sequence is not a common practice and that a legume or oilseed rape would have been more appropriate. However, the use of grass allowed investigating the effects of the application of OMF on this crop at a field scale and also linking the results from the other experimental scales used in this research; e.g. glasshouses studies, and at a later stage the lysimeters studies. From the research management perspective, the use of grass in Avenue Field appeared to be more consistent with the general objectives of this research and the need to produce technical data that would be of interest, and potentially applicable, in the Northwest region of England which is the main operating area of United Utilities plc.

Table 7.1: Crop and fertilisation records for commercial grown crops in Avenue and Chippies Fields for the crop seasons of 2004-05 to 2009-10.

Field	Year	Crop	Yield (t ha^{-1})	N-Fertilisation
Avenue	2004-05	Set-a-side	-	-
	2005-06	Oilseed rape	2.95	200 kg [N] ha^{-1}
	2006-07	Winter wheat	8.90	200 kg [N] ha^{-1}
	2007-08	Winter wheat	7.75	227 kg [N] ha^{-1}
	2008-09	Peas	3.37	-
	2009-10	Winter wheat	8.20	200 kg [N] ha^{-1}
Chippies	2004-05	Set-a-side	-	-
	2005-06	Peas	3.28	-
	2006-07	Winter wheat	9.00	200 kg [N] ha^{-1}
	2007-08	Oilseed rape	2.90	200 kg [N] ha^{-1}
	2008-09	Winter wheat	9.30	220 kg [N] ha^{-1}
	2009-10	Winter wheat	8.75	220 kg [N] ha^{-1}

A common practice at the College Farm is the application of nitrogen in solution using UAN (30% [N] w w^{-1}) which is applied with a sprayer. The nitrogen application rates shown in **Table 7.1** for the commercial crops were usually split into two applications of approximately 40% to 50% in the first dressing with the balance in the second dressing. The applications are conducted following the general guidance given in RB209 (MAFF, 2000) with respect to the timing of fertiliser application. **Figure 7.1** shows an overview of the College Farm at Silsoe and the two experimental sites located in Avenue and Chippies Fields respectively.

Figure 7.1: Overview of the College Farm (Cranfield University, Silsoe) and the experimental sites in [1] Avenue Field (rye grass), and [2] Chippies Field (winter wheat) [source: Google].

7.2.2 Details of the experiment

A total of 60 plots were marked out in February 2007 and February 2009 in Avenue and Chippies Fields respectively. The plots were surveyed using GPS equipment (Leica ATX1230 GNSS-GPRS Smart Rover fitted with Leica Smart-Net correction service). The work was subcontracted to Opti-cal Survey Equipment Ltd (Paulerspury, Northamptonshire, NN12 6LQ). The surveying allowed the re-location of the plots following the tillage operations in post-harvest. This made it possible for the continuation of the experiment at the sites ensuring the same fertiliser treatment was applied to each individual plot year on year. This was a key part of the work and it allowed investigating the effects of continuous fertiliser application on the fertility status of the soil and the effect upon the crop. The dimensions of the plots were 10 m^2 (2 m by 5 m) in Avenue Field and 6 m^2 (2 m by 3 m) in Chippies Field to allow all plots to fit in the designated experimental area. The layout of the field experiments and the treatments for individual plots for both sites is shown in **Appendix A.7.2**. Smaller size plots were required in Chippies Field to minimise the effect of the slope and changing soil type on the treatments. The crops were managed according to the standard farm practice, and with the exception of the fertiliser application, they received the same agronomic treatment (agrochemical applications) throughout the crop season as the rest of the commercial crop in the field. Wheat was sown every year between the second and third week of October at a rate of 150 kg [seeds] ha^{-1}. The wheat varieties used were Claire in Avenue Field and Nijinsky in Chippies Field, both classified as soft endosperm and NABIM Group 3 varieties (HGCA, 2008). A total of four different fertiliser materials were used in the studies so that OMF_{10}, OMF_{15} were compared with biosolids granules and urea.

A detailed description of the fertiliser products used was previously reported in **Chapter 3.** The fertilisers were hand-applied at rates ranging from 0 (control) to 250 kg [N] ha^{-1} at regular increments of 50 kg [N] ha^{-1}. The actual amounts of fertiliser applied on the plots are shown in **Appendix A.7.3**; these were different between-years due to the differences encountered in the concentration of nitrogen in the various fertiliser batches. The wheat crop was mechanically harvested using a Deutz-Fahr M660 plot combine harvester equipped with a device for bagging the grain from the plots (**Appendix A.7.4**). Grass was harvested manually using a four-square of 0.5 m^2 which was placed approximately in the centre of the plot and the grass cut at approximately 20 mm above the soil surface (Cordovil et al., 2007). Following the collection of the sample, a topper attached to a tractor was used to cut the grass of the entire experimental area to ensure re-growth was uniform both in and between-plots. The grass was cut three times in 2009 and two times in 2010. A third cut was not possible in the second year following establishment since the experiment was interrupted in August 2010. A completely randomised design was used and all treatments were replicated three times except for the controls (zero-fertiliser) and the plots receiving 250 kg [N] ha^{-1} which were replicated four and two times respectively. As highlighted earlier, this allowed fitting all plots in the designated experimental area. It also minimised the interference with the management of the surrounding commercial crop. In addition, it was possible to locate all plots on relatively uniform soil conditions hence reducing the effect of the slope and changing soil characteristics. **Figure 7.2** shows an overview of the experimental sites at the College Farm at Silsoe. The grass in Avenue Field was drilled on 30th March 2009 at a rate of 1.5 kg [seeds] ha^{-1} and emergence was recorded on 11th April 2009. The grass mix was made up of the following: 15% Molisto (hybrid rye grass), 30% Gandalf, 30% Premium, and 25% Fornax, all perennial rye grass (*Lolium perenne L.*). Drilling at a sowing depth of 10-15 mm is usually superior to broadcasting in light soils as it places the seed in contact with soil moisture and ensures a greater germination rate (Frame, 1992). Broadleaves weeds were controlled in post-emergence with MCPA applied at the manufacturer's recommended rate for rye grass in establishment.

Summary of experimental design: it comprised the use of four fertiliser materials (biosolids granules, OMF_{10}, OMF_{15} and urea) applied at rates ranging from zero (unfertilised control) to 250 kg [N] ha^{-1} at regular increments of 50 kg [N] ha^{-1}. The experimental sites were occupied with winter wheat 2006-07 and 2007-08 and rye grass 2009-10 (Avenue Field), and winter wheat 2008-09 and 2009-10 (Chippies Field). For Avenue Field (2006-07), in addition to the nitrogen rates mentioned above, the crop received 100 kg [N] ha^{-1} (UAN – 33% N solution) in the 1st dressing. All treatments were replicated 3 times except the unfertilised control plots and those treated with 250 kg [N] ha^{-1} which were replicated 4 and 2 times respectively.

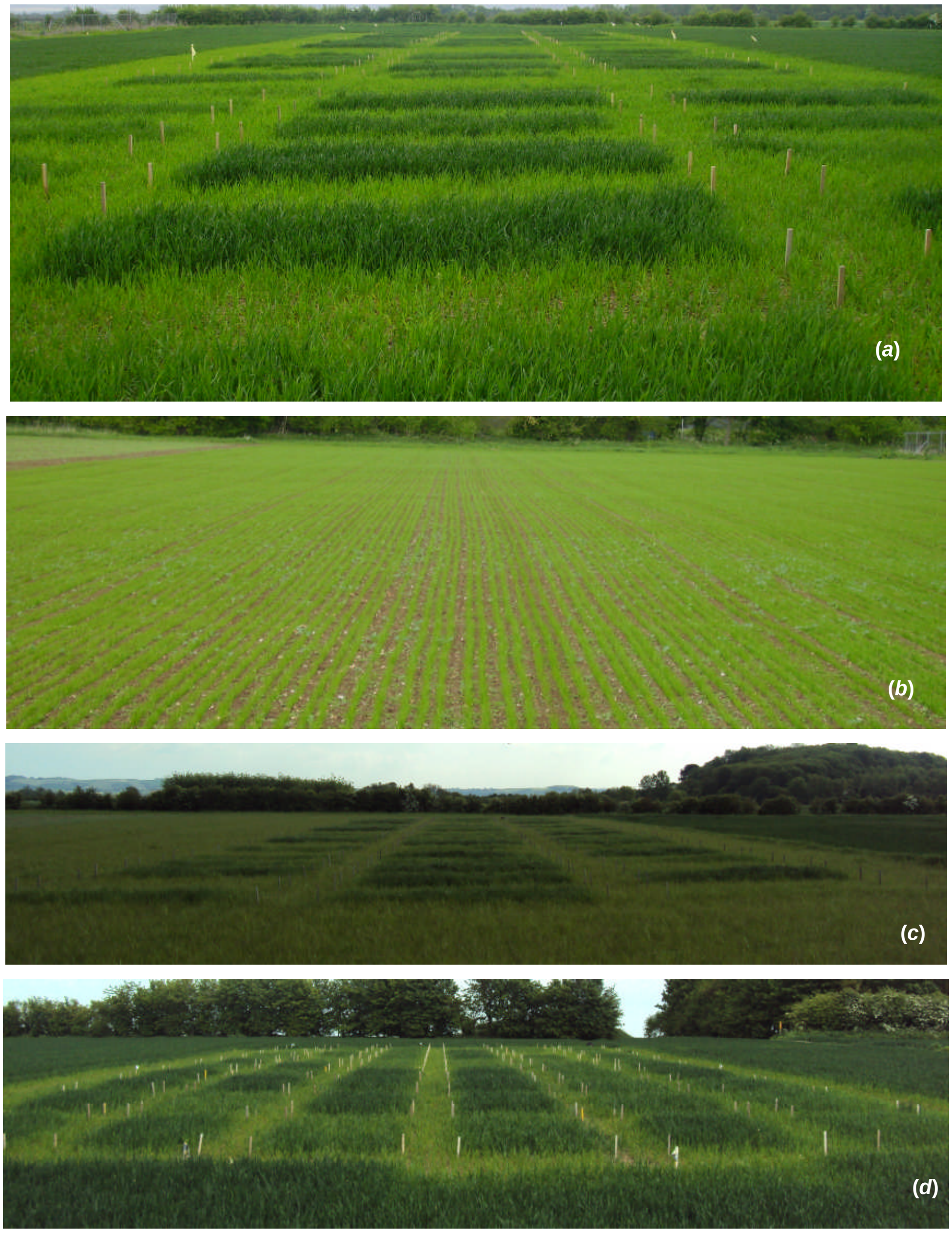


Figure 7.2: Overview of the field experiments; (*a*) winter wheat 2007-08 (Avenue Field), (*b*) rye grass in establishment in 2009 and (*c*) prior to the 1st cut in 2009 (Avenue Field), (*d*) 2nd winter wheat 2009-10 (Chippies Field).

7.2.3 Crops and soil measurements and analyses

The results of the soil chemical analyses conducted prior to the start of the experiment are presented in **Table 7.2.** These values represented the baseline level in the soil nutrient status at the time the experiments started. Soil sampling was conducted in February 2007 for Avenue Field and in March 2009 for Chippies Field.

The soil textural analysis for Avenue Field was reported in **Chapter 5** and corresponds to the sandy loam soil used for the incubation studies. As highlighted earlier, Chippies Field presented a relatively sandier and coarser texture than Avenue Field with 79% sand, 11% clay and 10% silt as determined by the pipette method (Avery and Bascomb, 1974; BS 1377 Part 2.0, 1990).

Table 7.2: Soil analyses (0-200 mm) conducted prior to the start of the experiments in Avenue and Chippies Fields at the College Farm, Silsoe (*SD*: standard deviation; n=3).

	Experimental field				
Determination	**Avenue**	***SD***	**Chippies**	***SD***	**Method**
Soil pH	7.11	0.04	7.09	0.04	MAFF (1986) Method No.: 32
SOM (%, w w^{-1})	3.87	0.05	3.43	0.12	MAFF (1986) Method No.: 56
C:N ratio	10.7	0.34	11.9	0.26	-
SMN (mg kg^{-1})	1.33	0.07	3.90	1.32	MAFF (1986) Method No.: 53
Extractable P (mg kg^{-1})	68.30	0.33	61.42	0.72	Olsen et al. (1954); BS 7755 Section 3.6 (1995)
Extractable P (mg l^{-1})	91.52	0.44	82.30	0.97	-
P-index	5	-	5	-	MAFF (2000)
Extractable K (mg kg^{-1})	211.7	1.44	-	-	MAFF (1986) Method No.: 63
Extractable K (mg l^{-1})	283.7	1.93	-	-	-
K-index	3	-	-	-	MAFF (2000)
Total C (%, w w^{-1})	1.59	0.07	1.51	0.06	BS 7755 Section 3.8 (1995)
Total N (%, w w^{-1})	0.149	<0.01	0.126	<0.01	Dumas (1831); BS EN 13654-2 (2001)
Total P (mg kg^{-1})	1070	-	-	-	US EPA Method No.: 3051; BS 7755-3.13 (1998)
Heavy metals (mg kg^{-1}):	-	-	-	-	US EPA Method No.: 3051; BS 7755-3.13 (1998) –
	-	-	-	-	[Determination of elements soluble in *aqua regia*]
Cd	0.17	<0.01	-	-	
Cu	0.01	<0.01	-	-	
Zn	0.05	<0.01	-	-	
Pb	0.02	<0.01	-	-	

In addition to the soil analyses listed in **Table 7.2**, a number of determinations were performed routinely in both the crops and the soils as shown in **Table 7.3.** Soil sampling was always conducted to a depth of 0.2 m. For wheat, crop yield is reported in kg [grain] ha^{-1} and the moisture content in the grain has been corrected to 15% (w w^{-1}) which is usually the upper level above which grain can be rejected due to the risk of mould and mycotoxins formation above this value (HGCA, ____). Total above-the-ground biomass in wheat was determined by cutting and weighting a four-square (0.5 m^2) sample of the crop at approximately 20 mm above the soil surface (Cordovil et al., 2007).

Harvest index is the ratio of grain weight to total plant weight (Sinclair, 1998). For simplicity, harvest index was determined as the ratio of grain weight to total above-the-ground biomass based on the weight of the grain and the crop biomass of the four-square sample. The weight of thousand grains (W_{1000}) was determined according to MAFF (1986; Method No.: 73). Another component of crop yield measured included the determination of the number of ears per m^2 (Wibberley, 2006) which was estimated based on the number of ears encountered on the four-square sample. Also for rye grass, four-square samples (0.5 m^2) cut at 20 mm above the ground (Cordovil et al., 2007) were collected and subsequently oven-dried at 60 degrees Celsius for 48 hours (MAFF, 1986; Method No.: 1) for determination of total above-the-ground biomass which is reported as grass yield in kg [DM] ha^{-1}.

Table 7.3: Details of soil (0-200 mm) and crop analyses conducted during the field experiments in Avenue $^{(*)}$ and Chippies $^{(**)}$ Fields. Methods of analysis are identical to those shown in Table 7.2.

Determination	Timing of sampling and analysis
Total N_{soil}	▪ Post-harvest wheat 2007-08 $^{(*)}$ ▪ End of experiment 2010 $^{(*); (**)}$
SMN	▪ Annually, before fertiliser application $^{(*); (**)}$ ▪ Annually, post-harvest wheat $^{(*); (**)}$ ▪ Annually, after last cut of grass $^{(*)}$
Extractable-P	▪ Post-harvest of wheat 2007-08 $^{(*)}$ ▪ Post harvest of wheat 2009-10 $^{(**)}$ ▪ End of experiment 2010 $^{(*); (**)}$
Extractable-K	▪ Post-harvest of wheat 2007-08 $^{(*)}$ ▪ End of experiment 2010 $^{(*)}$
Soil pH	▪ Post-harvest of wheat 2007-08 $^{(*)}$ ▪ Post harvest of wheat 2009-10 $^{(**)}$ ▪ End of experiment 2010 $^{(*)}$
SOM	▪ Post-harvest of wheat 2009-10 $^{(**)}$ ▪ End of experiment 2010 $^{(*)}$
Heavy metals in soil (Cd, Cu, Zn, Pb)	▪ End of experiment 2010 $^{(*)}$
Grain yield	▪ Wheat crop, all years $^{(*); (**)}$
Total N_{grain}	▪ Wheat, 2007-08 & 2009-10 $^{(*)}$
Total above-the-ground biomass	▪ Wheat, 2007-08 to 2009-10 $^{(*); (**)}$ & rye grass $^{(*)}$
Harvest index	▪ Wheat, 2007-08 to 2009-10 $^{(*); (**)}$
Weight 1000 grains (W_{1000})	▪ Wheat, 2007-08 to 2009-10 $^{(*); (**)}$
Ears per m^2	▪ Wheat, 2007-08 to 2009-10 $^{(*); (**)}$

7.2.4 Statistical analyses

Statistical analyses were undertaken to determine the effects of the treatments and the continuous application of organomineral fertilisers on crop yield and quality and also on the measured soil parameters. These included analysis of variance (ANOVA) and the use of the least significant differences to compare the means ($LSD_{[5\% \text{ level}]}$). The analysis of the data for the measured soil parameters was undertaken using a repeated measurement of analysis of variance (5% level) which allowed factoring in the effect of the time. The same approach was used for the grass to compare the yield obtained in individual cuts conducted within one specific year. In all cases, the statistical analyses were graphically assessed by means of residual plots. When residuals did not show a normal distribution, the dataset was normalised by means of a natural logarithm transformation or by removing the values that showed extreme residuals.

Non-linear regression analyses were used to investigate the relationship between nitrogen application rates and yield for both grass and wheat. The relationships between crop yield components (wheat) and nitrogen application rates were investigated by means of linear regression analyses. The regression analyses conducted for grass were undertaken for all individual cuts as well as the total annual yield which included three cuts in 2009 and two in 2010. The statistical analyses were conducted using GenStat Release 10.1 (2007) and the results are presented in detail in **Appendix A.7.5.**

7.3 Results and discussion

The results of the field experiments are reported in the following sections. The responses of the crops to the application of fertiliser are presented in **Sections 7.3.1** and **7.3.2** for winter wheat and rye grass respectively. The effects of the treatments on the soil and the results of the analysis of selected soil parameters are presented in **Section 7.3.3** and an overall discussion leading to the conclusions of this chapter is given in **Section 7.4** and **7.5** respectively. This discussion focuses upon the effects of the continuous application of biosolids, OMF and urea on the crops as well as the changes observed in the soil fertility status over the past four years of field studies.

7.3.1 Winter wheat

i. Pilot investigation

A pilot investigation on winter wheat (1st crop after oilseed rape – **Table 7.1**) was first conducted during the harvest season of 2006-07 in Avenue Field.

The production of OMF for the field experiments in the first year could not be completed until late April 2007 and a decision was made to apply a base nitrogen fertilisation to all plots using a mineral nitrogen source. This application coincided with the first nitrogen dressing conducted for the commercial field on 27th March 2007 with the crop at growth stage 24-25; i.e. main shoot and 4-5 tillers (Tottman and Broad, 1987). The fertiliser was applied with a sprayer at a rate equivalent to 100 kg [N] ha^{-1} using UAN (30% [N] w w^{-1} – solution). The sprayer was driven on the existing tramlines in the field and over the plots, and the fertiliser applied on the entire experimental area except the control plots. These were covered with plastics sheets which prevented the fertiliser solution from reaching the crop and the soil beneath and subsequently carefully removed to avoid leaking the fertiliser on the plots.

The application of biosolids, OMF_{10}, OMF_{15} and urea was conducted on 17th May 2007 approximately 3 weeks later than the second nitrogen dressing conducted for the rest of the commercial crop in the field. At this time, the crop was at growth stage 36-37; i.e. between 6th node and flag leaf just visible (Tottman and Broad, 1987). This second dressing should have been conducted at growth stage 30-31; i.e. early stem extension (Tottman and Broad, 1987) or approximately 2-3 weeks after the first nitrogen application in order to maximise the effect of the fertiliser on crop yield. The amounts of OMF_{10} and OMF_{15} applied in May 2007 were calculated on the basis of the products' formulation as specified in **Chapter 3** and not on the actual composition of the products since results of their chemical analyses were not available at the time the products were applied.

In addition, the amounts of biosolids applied were based on the biosolids' composition reported in **Chapter 3** which was the only information available at the time. The chemical analyses of biosolids, OMF_{10} and OMF_{15} reported in **Chapter 3** were made available after the fertilisers were applied. Since the OMF products were not made to specification, with nitrogen contents below those of their recommended formulations, the application of the products resulted in under-dosage of OMF-N in OMF-treated plots. Similarly, the plots treated with biosolids were over-dosed with biosolids-N. In order to correct the under-dosage of nitrogen in OMF-treated plots, a decision was made to conduct a third fertiliser application on these plots only. This was performed on 6th June 2007 with the crop at growth stage 41-42; i.e. flag leaf sheath extending (Tottman and Broad, 1987). It may be argued that this late application of fertiliser have only had a small effect on grain yield. However, their application ensured that both OMF and biosolids were applied on the site and that the effects on the soil could be investigated.

It also ensured that the experiment was consistent with the overall objectives of the work despite the differences in the timing of fertiliser applications with respect to the standard farm practices.

The crop responses to the application of fertiliser encountered for the crop season of 2006-07 are shown in **Figures 7.3** and **7.4** for OMF_{10}, OMF_{15} and urea, and biosolids respectively. The nitrogen application rate indicated on the figures (*x*-axis) includes the nitrogen applied as UAN in the first dressing and it should be read as the total nitrogen applied to the crop during the harvest season of 2006-07. Since the overall nitrogen application rates of biosolids-treated plots were different from those treated with OMF_{10}, OMF_{15} and urea, the statistical analyses had to be conducted separately. Comparisons could only be made between biosolids-treated plots and controls (zero-fertiliser) and, on a separate analysis, between the rest of the fertiliser materials used and the same control plots. It is expected, however, that these differences were not significant since the mean yield values for all treatments (excluding the controls) were of similar level across the whole experiment (10325, 10367, 10498, and 10751 kg [grain] ha^{-1} for biosolids, OMF_{10}, OMF_{15} and urea respectively) and certainly lower than the $LSD_{[5\%\ level]}$ values encountered in both analyses.

The statistical analysis revealed that there were significant differences in grain yield between the controls and the treatments (p-values <0.001). Overall, the application of fertiliser resulted in an increment in grain yield of *c*.4150 kg ha^{-1} with respect to the unfertilised crop (mean grain yields of 6332 and 10485 kg ha^{-1} for the control and the treatments respectively; $LSD_{[5\%\ level]}$ =934.4). This increment in biosolids-treated plots was *c*.3990 kg ha^{-1} which was also significant ($LSD_{[5\%\ level]}$ =750.8). In addition, the differences recorded in grain yield were nonsignificant for the effect of the nitrogen application rate (p=0.459), the fertiliser type (p=0.475) and the interaction between the two factors (p=0.269).

Similarly, the use of biosolids did not produce a significant effect with respect to the nitrogen application rate (p=0.135). These results suggested that the overall effect of the fertiliser type and the nitrogen application rate upon the yield of the crop were largely influenced by the application of UAN in the first nitrogen dressing. The effect was enhanced due to the type of fertiliser used (solution) and also the relatively high nitrogen rate applied (100 kg [N] ha^{-1}).

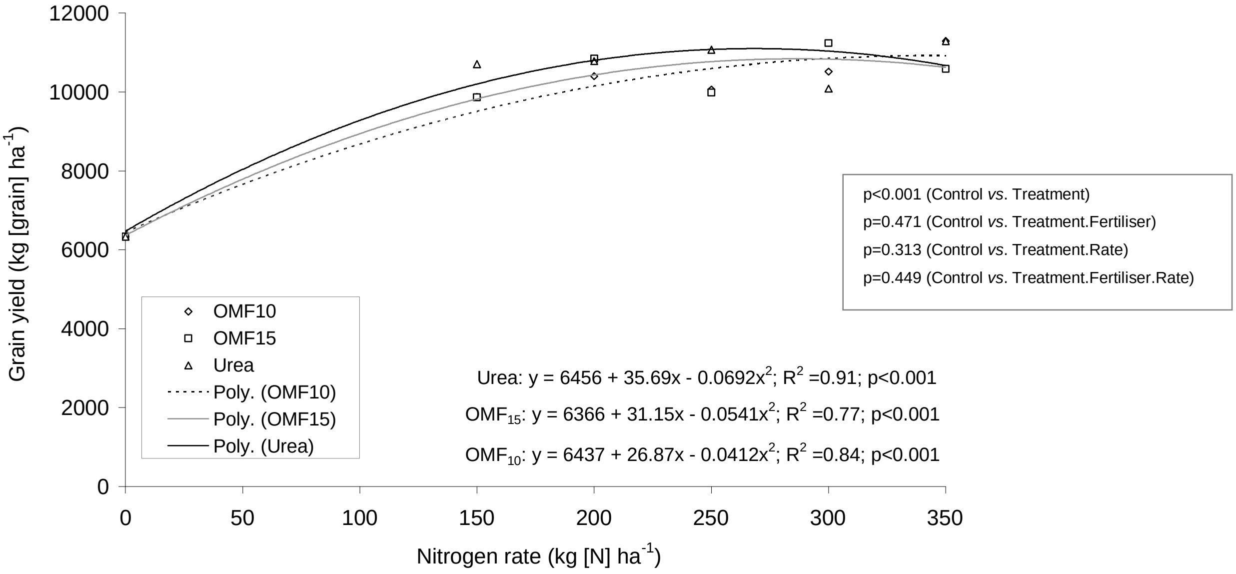


Figure 7.3: Relationship between nitrogen application rate and grain yield for winter wheat for the harvest season 2006-07 in Avenue Field (1st wheat) following application of OMF$_{10}$, OMF$_{15}$ and urea to the crop [LSD$_{[5\%\ \mathrm{level}]}$ =1699.0 (min. rep); LSD$_{[5\%\ \mathrm{level}]}$ =1551.0 (max-min. rep); LSD$_{[5\%\ \mathrm{level}]}$ =1387.2 (max. rep); n=3 except controls n=4, and plots treated with 350 (kg [N] ha^{-1}) n=2].

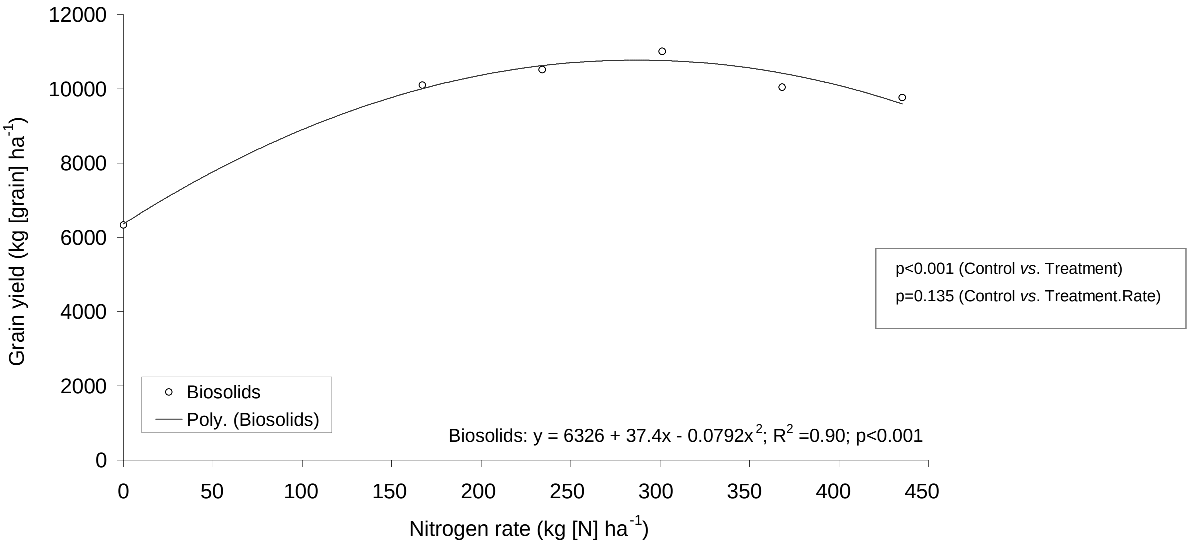


Figure 7.4: Relationship between nitrogen application rate and grain yield for winter wheat for the harvest season 2006-07 in Avenue Field (1st wheat) following application of biosolids to the crop [LSD$_{[5\%\ \mathrm{level}]}$ =1077.3 (max-min. rep); LSD$_{[5\%\ \mathrm{level}]}$ =963.6 (max. rep); n=3 except controls n=4, and plots treated with 435 (kg [N] ha^{-1}) n=2].

The information reviewed in **Chapter 2** indicated that maximum grain yields in winter wheat may be achieved with nitrogen fertilisation levels in the range of 190 to 240 kg [N] ha^{-1}. The lowest nitrogen rate used in the trials in 2006-07 was 150 kg [N] ha^{-1} which was close to the lower limit of the range mentioned above. Hence, the results obtained in 2006-07 appear to be reasonable as little increase in crop yield was obtained above this level of fertilisation. The differences in grain yield found at higher nitrogen application rates (>150 kg [N] ha^{-1}) were nonsignificant ($p>0.05$). This was also the case for biosolids-treated plots which were applied with even larger amounts of nitrogen (≥167 kg [N] ha^{-1}) than the other treatments.

To certain extent, the over-dosage of nitrogen applied on biosolids-treated plots explains, in terms of grain yield, the overall performance of the crop which resulted in similar yield levels as the rest of the treatments. It is also interesting to note that a significant decline in grain yield was not observed in any of the treatments even at the greatest nitrogen level used (350 and 435 kg [N] ha^{-1} for all fertilisers, excluding biosolids, and biosolids respectively). A possible explanation is with regards to the timing of application and the fact that only the early nitrogen application has had a significant effect in defining the potential yield of the crop given the conditions of this particular year (i.e. rainfall – see **Appendix A.7.1**).

A statistical analysis was later conducted to further examine the effect of the treatments only. It was suspected that differences between-treatments could not be detected as a result of the much larger effect of the control versus treatments. For this, the data corresponding to the control plots were removed from the dataset and the analysis re-run. However, the results of the statistical analysis revealed identical trends to the previous analysis conducted which included the full dataset (p-values of 0.494, 0.346, and 0.495 for the effect of the rate, the fertiliser type and the interaction between the factors respectively). The same results were observed when the unfertilised controls were removed from dataset for the analysis of the data corresponding to biosolids-treated plots only ($p=0.198$ for the effect of the rate). Indirectly, these results also suggested that crop yield was not influenced by varying amount of P_2O_5 and/or K_2O in relation to fixed amounts of nitrogen (considering that the concentration of phosphorus in OMF and biosolids were different). From the analysis of the data of this pilot investigation, it is clear that crop responses to the application of OMF were largely influenced by the application of UAN in the first dressing. It is also possible that a clear differential effect of the fertiliser type was not observed because the materials were ground prior to their soil application and the fact that they were applied at various stages in the crop cycle.

It is considered to be unlikely that the third nitrogen application, conducted on 6th June 2007, has had a significant effect on grain yield since the mineral nitrogen fraction applied with the fertiliser at this stage was relatively small (in relation to the total nitrogen applied). In addition, mineralisation of the organic-N fraction, as shown earlier in the incubation studies, is expected to have contributed little to grain yield at this stage, given the short period of time before the critical period of the crop was reached. This critical period, where potential yield is defined, occurs around pre-anthesis (Slafer and Andrade, 1993).

ii. Grain yield

The following sections (**7.3.1 ii-iv**) report on the results corresponding to the 2nd winter wheat in Avenue Field (2007-08), and the 1st and 2nd winter wheat crops in Chippies Field (2008-09 and 2009-10 respectively). In contrast with the previous crop season (2006-07), the fertilisers were always applied in a single dressing. This was performed despite the standard farm practice which would dictate splitting the application of nitrogen into two or three dressings depending upon the recommended rate (**Chapter 2**). There were, however, some practical advantages in conducting a single application; firstly, it reduced the workload in the field. Secondly, since the fertilisers were applied manually, the uniformity of distribution was improved when larger amounts of material were applied, especially for plots receiving lower nitrogen application rates or those having a more concentrated nitrogen fertiliser. This was also the case for Chippies Field where the size of the plots was reduced from 10 m^2 to 6 m^2. For the 2nd wheat in Avenue Field, the fertilisers were applied to all plots on 3rd April 2008 with the crop at growth stage 25-26; main shoot and 5-6 tillers (Tottman and Broad, 1987). It may be argued that this application was slightly delayed with respect to the recommended date (**Chapter 2**); however, low temperatures and snow were recorded in late March 2008 at the site which prevented the application of nitrogen fertiliser.

Coincidently, in Chippies Field, the fertilisers were applied on the same the date (24th March) both years 2008-09 and 2009-10 respectively (crop at growth stage 23-24 and 21-22; main shoot plus three to four tillers, and main shoot plus one to two tillers for the 1st and the 2nd wheat respectively; Tottman and Broad, 1987). The crop responses to applied nitrogen are shown in **Figures 7.5-7.7** for Avenue and Chippies Fields respectively.

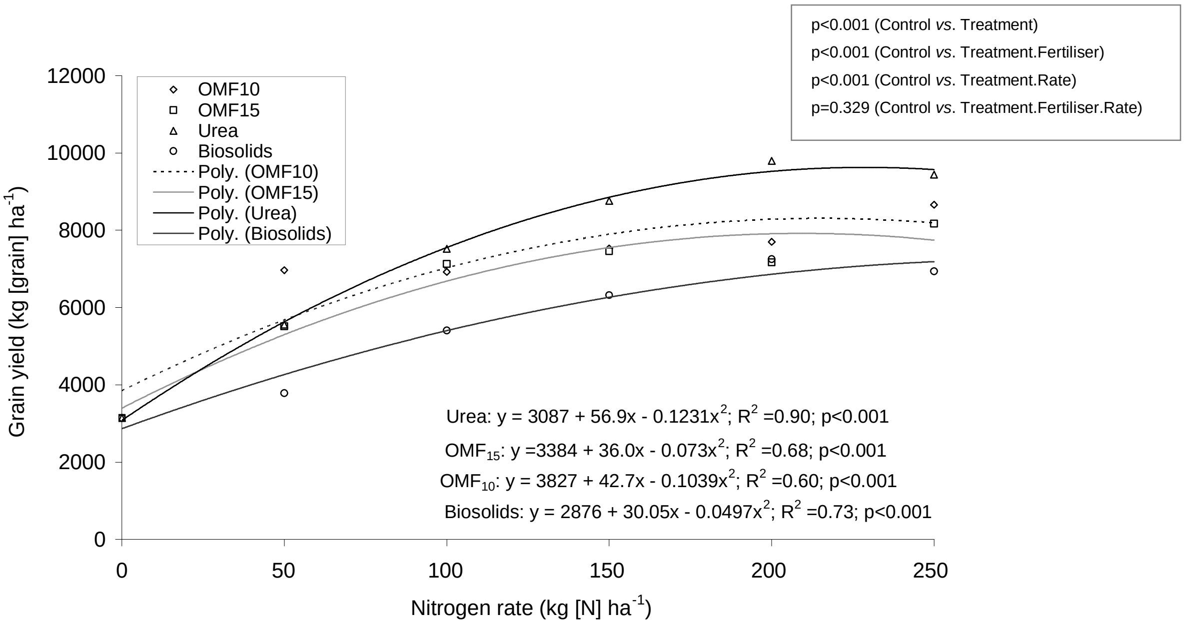


Figure 7.5: Relationship between nitrogen application rate and grain yield for winter wheat for the harvest season 2007-08 in Avenue Field (2nd wheat) following application of biosolids granules, OMF_{10}, OMF_{15} and urea to the crop [$LSD_{[5\% \text{ level}]}$ =2019.0 (min. rep); $LSD_{[5\% \text{ level}]}$ =1843.1 (max-min. rep); $LSD_{[5\% \text{ level}]}$ =1648.5 (max. rep)); n=3 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=2].

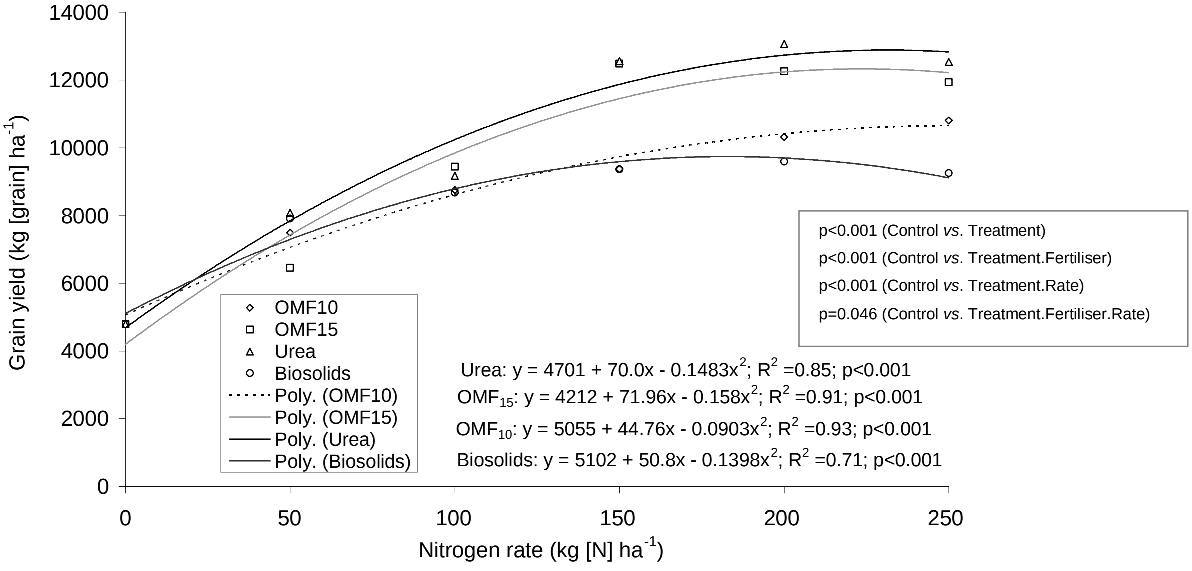


Figure 7.6: Relationship between nitrogen application rate and grain yield for winter wheat for the harvest season 2008-09 in Chippies Field (1st wheat) following application of biosolids granules, OMF_{10}, OMF_{15} and urea to the crop [$LSD_{[5\% \text{ level}]}$ =2317.4 (min. rep); $LSD_{[5\% \text{ level}]}$ =2115.5 (max-min. rep); $LSD_{[5\% \text{ level}]}$ =1892.1 (max. rep)); n=3 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=2].

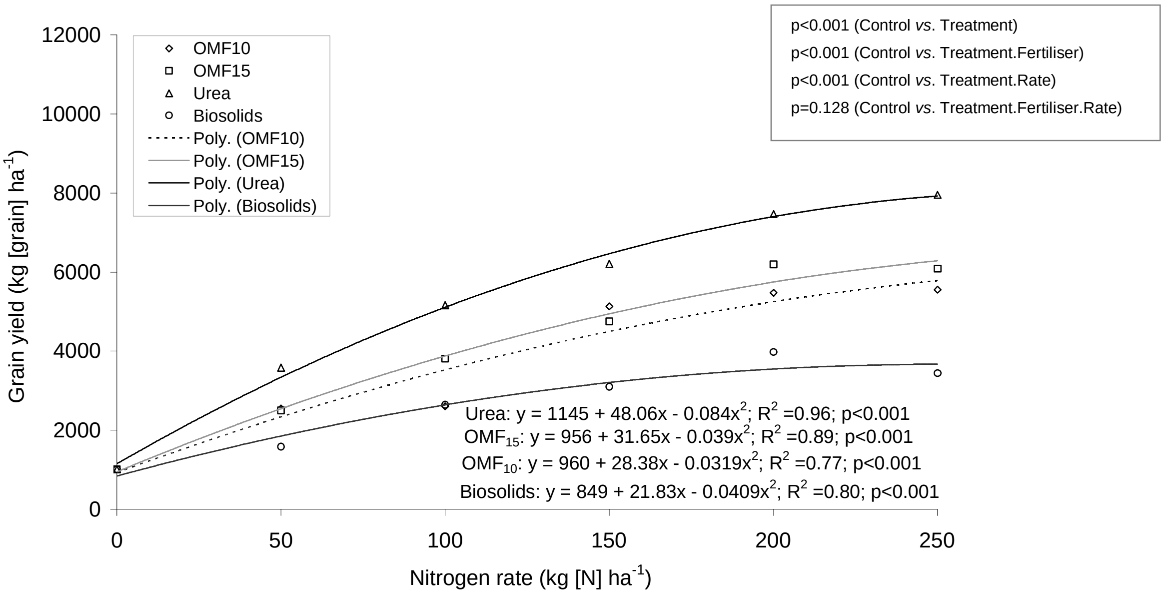


Figure 7.7: Relationship between nitrogen application rate and grain yield for winter wheat for the harvest season 2009-10 in Chippies Field (2nd wheat) following application of biosolids granules, OMF_{10}, OMF_{15} and urea to the crop [$LSD_{[5\% \text{ level}]}$ =1347.5 (min. rep); $LSD_{[5\% \text{ level}]}$ =1230.1 (max-min. rep); $LSD_{[5\% \text{ level}]}$ =1100.3 (max. rep)); n=3 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=2].

For the 2nd wheat in Chippies Field (2009-10), the number of tillers observed at around the same date was lower compared to the previous year as recorded by visual assessment. In addition, the crop showed some damage by rabbits which resulted in lower number of plants per square meter compared with the first year. This is thought to have delayed the re-growth of the crop in early spring compared, for example, with other wheat crops grown on the farm; e.g. those on heavier soils, also as recorded by visual assessment.

The statistical analysis for Avenue Field (2007-08) showed that there were significant differences in grain yield between the controls and the treatments ($p<0.001$). The application of fertiliser resulted in an overall increase of 3975 kg [grain] ha^{-1} with respect to the unfertilised control (mean values of 3145 and 7120 kg [grain] ha^{-1} for the control and the treatments respectively; $LSD_{[5\% \text{ level}]}$ =1196.5). In addition, significant differences were found for the effect of the fertiliser type and the nitrogen application rates used (p-values <0.001 respectively). However, the interaction between the fertiliser type and the nitrogen rate did not show a significant effect ($p=0.329$). With respect to the fertiliser type, the effects were mainly due to the use of urea and biosolids granules which produced, respectively, significantly higher and lower grain yields than the two OMF products as shown in the corresponding graph.

It is interesting to note that, although the effect not being significant, OMF_{10} produced, overall, larger grain yields than OMF_{15} (mean values of 7477 and 7010 kg [grain] ha^{-1} respectively; $LSD_{[5\%\ level]}$ =763.1). This may be attributable to poorer physical quality of OMF_{15} compared with OMF_{10} as reported in **Chapter 3** (OMF_{15} showed *c*.16% of the particles <1.18 mm and *c*.3.5% above 9.5 mm compared to <3% and <0.75% approximately in OMF_{10}, respectively). This affected the uniformity of nutrients distribution, particularly nitrogen, which was reflected on the yields obtained.

The analysis of the data for the 1st wheat at Chippies Field (**Figure 7.6**) showed that there were significant differences in grain yield between the control and the treatments (p<0.001). Overall, the application of fertiliser resulted in crop yield being increased by *c*.5100 kg [grain] ha^{-1} with respect to the unfertilised control (mean crop yields equivalent to 4796 and 9893 for the control and the treatments respectively; $LSD_{[5\%\ level]}$ =1373.3). In addition, there were significant differences in grain yield with respect to the nitrogen application rates used (p<0.001), the fertiliser type (p<0.001) and the interaction between the fertiliser type and the nitrogen rate (p=0.046). There appears to be a clear effect of the nitrogen concentration in the fertiliser, and in particular, the readily available nitrogen content, on the resultant crop yields. In this respect, the grain yield was increased when a more concentrated nitrogen source was used.

Overall, across the whole experiment, the highest levels of grain yield in Chippies Field (2008-09) were obtained in urea-treated plots. The yield obtained with biosolids granules was approximately double than that of the unfertilised controls but still significantly lower than OMF_{10} and OMF_{15} (p<0.001). It is important to note that the interaction between the fertiliser type and the nitrogen rate produced a significant effect (p=0.046). This relationship had not been observed in the previous two years in Avenue Field. Possibly, this effect was not shown in 2006-07 as a result of the base nitrogen application with UAN (100 kg [N] ha^{-1}), the timing of fertiliser application and also the quality of the OMF products used which had similar compositions (**Chapter 3**). There was also a possibility that the high nitrogen rates used in 2006-07 (**Figures 7.4-7.5**) had resulted in residual nitrogen in the soil which was used by the crop the following year (2007-08); hence, masking the effects of any interaction between fertiliser type and nitrogen rates. Unfortunately, there is not SMN data collected before the fertiliser application in 2007-08 for Avenue Field for which this statement cannot be fully supported. However, there is evidence from the incubation studies (**Chapter 5**) which suggested that mineralisation of organic OMF-N would progress beyond the harvest of the crop.

The data obtained for the 2nd wheat crop (2009-10) at Chippies Field (**Figure 7.7**) showed a similar pattern to that presented for 2008-09 despite the consistently lower level of grain yields encountered overall in the second year. Overall, the application of fertiliser increased grain yield by *c.*3350 kg [grain] ha^{-1} with respect to the unfertilised crop (mean grain yields were 1011 and 4377 kg [grain] ha^{-1} for the control and the treatments respectively; $LSD_{[5\% \text{ level}]}$ =798.6; p<0.001). Significant differences in grain yield were also found with respect to the nitrogen application rate (p<0.001) and the fertiliser types (p<0.001) whereas the interaction between the nitrogen rate and the fertiliser type did not show a significant effect (p=0.128).

To some extent, the lower yields obtained in 2009-10 compared with 2008-09 can be explained by the fact that it was a second wheat crop which has naturally lower yield potential than a first crop as shown in Johnston and Poulton (2009) for the long-term experiments conducted at Rothamsted with winter wheat *cv.* Hereward grown continuously and in rotation. Johnston and Poulton (2009) reported that a significant increase in grain yield (by *c.*2 t [grain] ha^{-1} for *cv*. Hereward fertilised with 192 kg [N] ha^{-1}) was obtained when a two years break from wheat was introduced at Broadbalk for the period 1996-2000. The period between April and July 2010 was significantly drier than the same period in 2009 (**Appendix A.7.1**). The total rainfall recorded for the period was 152.8 mm in 2009 and 70.6 mm in 2010 (Met Office, 2010). Smith and Trafford (1976) had reported a mean rainfall of 184 mm for the same period based on historic rainfall data for Area 28. Drier soil conditions in the spring could have affected the mineralisation rate of biosolids-N and the organic OMF-N; hence, reducing nitrogen availability N-uptake by the crop and limiting crop growth and development. Since OMF_{10} and OMF_{15} were not strictly made to specification (**Chapter 3**) a larger proportion of organic-N was applied at any given rate of nitrogen which could have also compromised the availability of N to the crop.

The regression analyses undertaken showed significant relationships (p-values <0.001) between the nitrogen application rates and crop yield when a quadratic model was fitted to the data (**Appendix A.7.5**). However, for the data corresponding to the second wheat crops, the estimates of parameters for the square term (i.e. N-rate square) in biosolids, OMF_{10} and OMF_{15} did not show significant effects (t_{pr}-values >0.05). By eliminating the quadratic term from the model and converting it into a linear one and subsequently re-running the analysis, the regression remained significant for both the model and the linear term. This means that the relationship between the nitrogen application rate and crop yield in second wheat crops fertilised with biosolids, OMF_{10} and OMF_{15} can also be explained by a linear function for the range of nitrogen rates used in this experiment.

This effect was not observed for urea which always showed significance for the square term. Then, it is possible that when using biosolids or OMF in a 2nd wheat crop, the maximum grain yields would be achieved at larger nitrogen fertilisation levels than those shown in **Table 7.4a** which were estimated from a quadratic function. Having acknowledged these relationships, it can be seen from the equations shown in **Figures 7.3-7.7** that quadratic functions can still be fitted and gave acceptable fits (R^2>0.60) for all the fertiliser materials used. It was also shown that the coefficients for the quadratic term were always negative which indicated that the slopes of the curves were negative and therefore a peak in the response occurred after which subsequent increments in the nitrogen rate did not result in increasing crop yield. In this respect, Morrison et al. (1980) highlighted that, in their study, although the quadratic term was statistically nonsignificant, the quadratic regression provided a more satisfactory biological description.

In addition, reported evidence from previous crop trials indicated that the relationship between applied nutrients and crop yield can usually be explained by non-linear functions; e.g. Mitscherlich equation, square-root formula and quadratic curve (FAO, 1966; Helyar and Godden, 1977; Sparrow, 1979). The work reported by Abraham and Rao (1965) based on a large body of fertiliser trials' data showed that, in most circumstances, quadratic equations produced reasonable fits. By contrast, the work of Boyd et al. (1976) indicated that better fits were found by intersecting two straight lines and that the model also resulted in the least residual mean square compared with other models. The results and the correspondent fits of response curves were often influenced by the type of crop being tested and the level of fertilisation (Sparrow, 1979).

In a later study, Johnston and Poulton (2009) highlighted that the yield response to applied nitrogen fertiliser for *cv.* Hereward (Broadbalk Experiment, Rothamsted) in rotation was curvilinear where crop yield reached a maximum and then it decreased above certain level of nitrogen application ($\geq$192 kg [N] ha^{-1}). An advantage of quadratic functions is that they are simple to fit and admit data showing an actual decline in crop yield with increasing fertiliser dressings which cannot be shown with; for example, the Mitscherlich curve (FAO, 1966). On this basis, the use of the equations shown in **Figures 7.3-7.7** to describe these relationships can be justified to provide estimates of the nitrogen application rate (N_{max}) at which the maximum yields (Y_{max}) are obtained. The procedure for their calculation was previously reported in **Chapter 2** and it is based on the method used by James and Godwin (2003). The calculated maximum grain yields are shown in **Table 7.4a**.

Table 7.4a: Maximum grain yields (Y_{max}) obtained for winter wheat between 2006-07 & 2009-10 and nitrogen application rates (N_{max}) required for maximum yield for the four fertiliser types used in the trials [Values expressed in kg [N] ha^{-1} and kg [grain] ha^{-1}; *SD*: standard deviation]. Data derived from the yield to nitrogen response curves.

Treatment/	**Biosolids**		**OMF_{10}**		**OMF_{15}**		**Urea**	
Year	**N_{max}**	**Y_{max}**	**N_{max}**	**Y_{max}**	**N_{max}**	**Y_{max}**	**N_{max}**	**Y_{max}**
2006-07	235.9	10734	326.1	10818	287.9	10849	257.9	11057
2007-08	302.3	7418	205.5	8214	246.6	7823	231.1	9662
2008-09	181.7	9716	247.8	10602	227.7	12405	236.0	12961
2009-10	266.9	3761	444.8	7272	405.8	7377	286.1	8019
Mean	**246.7**	**7907.8**	**306.1**	**9226.5**	**292.0**	**9613.8**	**252.8**	**10425.1**
SD	**51.13**	**3092.4**	**105.14**	**1757.7**	**79.91**	**2281.0**	**25.07**	**2097.8**

Table 7.4b shows the mean grain yield ($\overline{Y}$) obtained in biosolids-treated plots each year and the differential yield ($\Delta\overline{Y}$) in the other treatments relative to that of biosolids. $\Delta\overline{Y}$ was expressed in kg [grain] ha^{-1} and also in percentage of the yield relative to biosolids-treated plots. This table shows that on average over the four years' trial, the use of OMF result in grain yield being increased by approximately 12%, 23% and 42% compared with biosolids. The high values of N_{max} encountered for OMF_{10} and OMF_{15} in 2009-10 could be the result of an artefact of assuming quadratic relationships between the nitrogen application rate and grain yield for that particular year and treatments for which the data should be treated with caution.

Table 7.4b: Differential mean yield ($\Delta\overline{Y}$; kg [grain] ha^{-1}) and relative yield (% $\overline{Y}$ of biosolids-treated plots) for winter wheat between 2006-07 & 2009-10 [*SD*: standard deviation].

Treatment/	**Biosolids**		**OMF_{10}**		**OMF_{15}**		**Urea**	
Year	$\overline{Y}$	**%**	$\Delta\overline{Y}$	**%**	$\Delta\overline{Y}$	**%**	$\Delta\overline{Y}$	**%**
2006-07	10325	100	42	100.5	173	101.7	426	104.1
2007-08	5869	100	1608	127.4	1142	119.4	2257	138.5
2008-09	8931	100	317	103.5	1485	116.6	2049	122.9
2009-10	2911	100	1258	143.2	1578	154.2	3028	204.0
Mean	**7009**	**100**	**806**	**111.5**	**1094**	**123.0**	**1940**	**142.4**
SD	**3305.7**	**-**	**746.4**	**20.3**	**642.3**	**22.2**	**1093.7**	**43.4**

iii. Nitrogen use efficiency (NUE)

The methods commonly used for measuring the nitrogen use efficiency were briefly discussed in **Chapter 2.** The values of NUE encountered for the harvest seasons of 2006-07 to 2009-10 are summarised in **Table7.5a-d**.

Table 7.5a: Nitrogen use efficiency (NUE) for applied fertiliser on winter wheat expressed as an agronomic efficiency (A_E), nitrogen recovery efficiency in the grain (R_N) and a partial factor productivity of applied nitrogen (I_P) for the harvest season of 2006-07.

Biosolids-N				**2006-07**			
applied (kg ha^{-1})	**0**	**167.1**	**234.1**	**301.2**	**368.3**	**435.3**	**N_{max} =235.9**
Yield (kg ha^{-1})	6332	10102	10517	11010	10043	9764	**Y_{max} =10734**
A_E (kg [grain] kg^{-1} [N])	-	22.56	17.88	15.53	10.08	7.88	**18.66**
R_N (%)	-	44.47	38.68	35.29	23.91	21.78	-
I_P (kg [grain] kg^{-1} [N])	-	60.45	44.93	36.55	27.27	22.43	**45.50**
OMF_{10}-N				**2006-07**			
applied (kg ha^{-1})	**0**	**150**	**200**	**250**	**300**	**350**	**N_{max} =326.1**
Yield (kg ha^{-1})	6332	9876	10339	10061	10516	11290	**Y_{max} =10818**
A_E (kg [grain] kg^{-1} [N])	-	23.63	20.34	14.92	13.95	14.17	**13.76**
R_N (%)	-	46.69	43.80	34.08	34.80	35.35	-
I_P (kg [grain] kg^{-1} [N])	-	65.84	52.00	40.24	35.05	32.26	**33.17**
OMF_{15}-N				**2006-07**			
applied (kg ha^{-1})	**0**	**150**	**200**	**250**	**300**	**350**	**N_{max} =287.9**
Yield (kg ha^{-1})	6332	9864	10845	9981	11241	10586	**Y_{max} =10849**
A_E (kg [grain] kg^{-1} [N])	-	23.55	22.57	14.60	16.36	12.15	**15.69**
R_N (%)	-	48.50	52.91	34.77	39.41	32.41	-
I_P (kg [grain] kg^{-1} [N])	-	65.76	54.23	39.92	37.47	30.25	**37.69**
Urea-N				**2006-07**			
applied (kg ha^{-1})	**0**	**150**	**200**	**250**	**300**	**350**	**N_{max} =257.9**
Yield (kg ha^{-1})	6332	10705	10783	11070	10087	11288	**Y_{max} =11098**
A_E (kg [grain] kg^{-1} [N])	-	29.15	22.26	18.95	12.52	14.16	**18.33**
R_N (%)	-	58.79	59.00	45.34	33.51	33.34	-
I_P (kg [grain] kg^{-1} [N])	-	71.37	53.92	44.28	33.62	32.25	**42.88**

Table 7.5b: Nitrogen use efficiency (NUE) for applied fertiliser on winter wheat expressed as an agronomic efficiency (A_E), nitrogen recovery efficiency in the grain (R_N) and a partial factor productivity of applied nitrogen (I_P) for the harvest season of 2007-08.

Biosolids-N				**2007-08**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =302.3**
Yield (kg ha^{-1})	3145	3788	5404	6322	7251	6937	**Y_{max} =7418**
A_E (kg [grain] kg^{-1} [N])	-	12.86	22.59	21.18	20.53	15.17	**14.14**
R_N (%)	-	7.92	33.86	27.52	31.27	27.28	-
I_P (kg [grain] kg^{-1} [N])	-	75.76	54.04	42.15	36.26	27.75	**24.54**
OMF_{10}-N				**2007-08**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =205.5**
Yield (kg ha^{-1})	3145	6968	6920	7532	7700	8658	**Y_{max} =8214**
A_E (kg [grain] kg^{-1} [N])	-	76.46	37.75	29.25	22.78	22.05	**24.67**
R_N (%)	-	-	53.13	45.82	38.71	38.82	-
I_P (kg [grain] kg^{-1} [N])	-	139.39	69.20	50.21	38.50	34.63	**39.97**
OMF_{15}-N				**2007-08**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =246.6**
Yield (kg ha^{-1})	3145	5512	7127	7458	7171	8170	**Y_{max} =7822**
A_E (kg [grain] kg^{-1} [N])	-	47.34	39.82	28.75	20.13	20.10	**18.97**
R_N (%)	-	61.68	53.20	44.70	33.90	36.53	-
I_P (kg [grain] kg^{-1} [N])	-	110.24	71.27	49.72	35.86	32.68	**31.72**
Urea-N				**2007-08**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =231.1**
Yield (kg ha^{-1})	3145	5557	7518	8758	9792	9440	**Y_{max} =9662**
A_E (kg [grain] kg^{-1} [N])	-	48.24	43.73	37.42	33.24	25.18	**28.20**
R_N (%)	-	65.71	68.60	63.52	60.04	47.32	-
I_P (kg [grain] kg^{-1} [N])	-	111.14	75.18	58.39	48.96	37.76	**41.81**

Table 7.5c: Nitrogen use efficiency (NUE) for applied fertiliser on winter wheat expressed as an agronomic efficiency (A_E) and a partial factor productivity of applied nitrogen (I_P) for the harvest season of 2008-09.

Biosolids-N				**2008-09**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =181.7**
Yield (kg ha^{-1})	4796	7913	8636	9365	9597	9254	**Y_{max} =9716**
A_E (kg [grain] kg^{-1} [N])	-	62.34	38.40	30.46	24.01	17.83	**27.08**
I_P (kg [grain] kg^{-1} [N])	-	156.26	86.36	62.43	47.99	37.02	**53.48**
OMF_{10}-N				**2008-09**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =247.8**
Yield (kg ha^{-1})	4796	7496	8752	9373	10323	10809	**Y_{max} =10601**
A_E (kg [grain] kg^{-1} [N])	-	54.00	39.56	30.51	27.64	24.05	**23.43**
I_P (kg [grain] kg^{-1} [N])	-	149.92	87.52	62.49	51.62	43.24	**42.78**
OMF_{15}-N				**2008-09**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =227.7**
Yield (kg ha^{-1})	4796	6461	9442	12486	12261	11936	**Y_{max} =12405**
A_E (kg [grain] kg^{-1} [N])	-	33.30	46.46	51.27	37.33	28.56	**33.42**
I_P (kg [grain] kg^{-1} [N])	-	129.22	94.42	83.24	61.31	47.74	**54.48**
Urea-N				**2008-09**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =236.0**
Yield (kg ha^{-1})	4796	8081	9176	12559	13066	12534	**Y_{max} =12961**
A_E (kg [grain] kg^{-1} [N])	-	65.70	43.80	51.75	41.35	30.95	**34.60**
I_P (kg [grain] kg^{-1} [N])	-	161.62	91.76	83.73	65.33	50.14	**54.92**

Table 7.5d: Nitrogen use efficiency (NUE) for applied fertiliser on winter wheat expressed as an agronomic efficiency (A_E) and a partial factor productivity of applied nitrogen (I_P) for the harvest season of 2009-10.

Biosolids-N				**2009-10**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =266.9**
Yield (kg ha^{-1})	1011	1578	2638	3099	3975	3441	**Y_{max} =3762**
A_E (kg [grain] kg^{-1} [N])	-	11.34	16.27	13.92	14.82	9.72	**10.31**
I_P (kg [grain] kg^{-1} [N])	-	31.56	26.38	20.66	19.88	13.76	**14.09**
OMF_{10}-N				**2009-10**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =444.8**
Yield (kg ha^{-1})	1011	2545	2604	5131	5473	5551	**Y_{max} =7272**
A_E (kg [grain] kg^{-1} [N])	-	30.68	15.93	27.47	22.31	18.16	**14.08**
I_P (kg [grain] kg^{-1} [N])	-	50.90	26.04	34.21	27.31	22.20	**16.35**
OMF_{15}-N				**2009-10**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =405.8**
Yield (kg ha^{-1})	1011	2498	3457	4747	6192	6082	**Y_{max} =7377**
A_E (kg [grain] kg^{-1} [N])	-	29.74	24.46	24.91	25.91	20.28	**15.69**
I_P (kg [grain] kg^{-1} [N])	-	49.96	34.57	31.65	30.96	24.33	**18.18**
Urea-N				**2009-10**			
applied (kg ha^{-1})	**0**	**50**	**100**	**150**	**200**	**250**	**N_{max} =286.1**
Yield (kg ha^{-1})	1011	3580	5161	6205	7468	7955	**Y_{max} =8019**
A_E (kg [grain] kg^{-1} [N])	-	51.38	41.50	34.63	32.29	27.78	**24.50**
I_P (kg [grain] kg^{-1} [N])	-	71.60	51.61	41.37	37.34	31.82	**28.03**

The values presented in the tables were calculated using the difference methods which include the agronomic efficiency (A_E) and the apparent nitrogen recovery (R_N). The partial factor productivity of applied nitrogen (I_P) was also estimated to provide an indication of the ratio kg of grain produced to kg of nitrogen applied (see **Section 2.6.11** for further details).

The apparent nitrogen recoveries were calculated for the 1st and 2nd wheat crops in Avenue Field (2006-07 & 2007-08 respectively), since total nitrogen in grain (TN_{grain}) was only determined on grain samples taken in the first two years of the trials. In addition, as nitrogen was not determined in the straw, the values reported in the tables correspond to the percentage nitrogen recovery in grain only. The agronomic efficiency and the partial factor productivity of applied nitrogen were calculated for the whole range of nitrogen application rates used and also for the maximum grain yields shown in **Table 7.4**. In general, the apparent nitrogen recovery (R_N), the agronomic efficiency (A_E) and the partial factor productivity (I_P) of applied nitrogen tended to increase when a more concentrated nitrogen source was used. An exception to this was observed for OMF_{15} compared with OMF_{10} for 2008 which was attributed to the relatively lower physical quality of the material in the former compared to the latter. This effect was observed for all three indexes on average over the range of nitrogen application rates. Urea showed consistently higher NUE indexes compared with the other treatments in most circumstances.

The analysis of TN_{grain} (2006-07) showed overall significant differences between the control and the treatments ($p<0.001$). The application of fertiliser increased TN_{grain} by *c*.30% compared with the unfertilised control (mean values of 1.310 and 1.714 % (w w^{-1}) TN_{grain} for the control and the treatments respectively; $LSD_{[5\% \text{ level}]}$ =0.076). Significant differences in TN_{grain} were also found with respect to the fertiliser type ($p=0.004$) and the nitrogen application rate ($p<0.001$) whereas the interaction between the two factors was found to be nonsignificant ($p=0.10$).

The relationship between the nitrogen application rate and TN_{grain} is shown in **Figure 7.8**. Overall, and despite the larger nitrogen application rates, the use of biosolids showed relatively lower TN_{grain} values than OMF_{10} and the same was observed between OMF_{15} and urea; the latter showed consistently higher TN_{grain} than the rest of the fertiliser materials. The increase in TN_{grain} was significantly ($p=0.007$) associated with the nitrogen application rates used, with values of TN_{grain} in the range of 1.571 to 1.819% (w w^{-1}) as shown earlier. A similar relationship between nitrogen application rate (range 0-250 kg [N] ha^{-1}) and TN_{grain} had also been reported by James (2000). The 2nd wheat crop in Avenue Field showed a similar pattern to that of the previous year where the control plots resulted in significantly lower TN_{grain} compared with the treated plots ($p<0.001$). The application of fertiliser to the 2nd wheat crop increased TN_{grain} by *c*.10% compared with the unfertilised control. Interestingly, the control crop resulted both years in almost identical levels of TN_{grain} (1.310 and 1.314% [w w^{-1}] TN_{grain}).

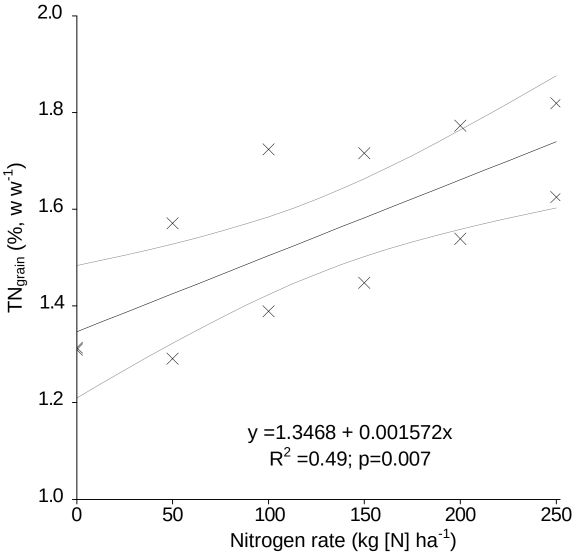


Figure 7.8: Relationship between nitrogen application rate and total nitrogen in grain (TN_{grain}) for winter wheat for the crop seasons of 2006-07 and 2007-08 in Avenue Field. The two curves on both sides of the fitted line represent its 95% confidence interval. Mean values across the whole experiment [n=12 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=8].

This suggested that the larger value obtained overall in the treated plots in the first year was influenced by the use of UAN in the first nitrogen dressing in 2006-07. In the second wheat crop, significant differences were also found with respect to the fertiliser type and the nitrogen application rate used (p-values <0.001) whereas the interaction between the two factors was found to be nonsignificant (p=0.073). The application of OMF_{15} produced overall a similar, though slightly lower, level of TN_{grain} than OMF_{10} whereas the use of biosolids and urea resulted in consistently lower and higher TN_{grain} levels respectively than the two OMF. The increase in the nitrogen rate (range 50-250 kg [N] ha^{-1}) markedly increased TN_{grain} but to a lesser extent (range 1.291-1.625 % (w w^{-1}) TN_{grain}; $LSD_{[5\% \text{ level}]}$ =0.044) compared with the values obtained for the first wheat crop. The relative increase in TN_{grain} observed in urea-treated plots compared with the rest of the treatments can be also attributable to enhanced nitrogen uptake as a result of increased SMN (derived from the fertiliser applied). Research (Knowles and Watkin, 1931; Gasser and Thorburn, 1972) has shown that nitrogen uptake from the soil continues until plant maturity (or senescence; e.g. Daigger et al., 1976; Gregory et al., 1979) despite the overall decline in the nitrogen concentration in plant which occurs as a result of the slower rate of N assimilation in relation to C (Harper et al., 1987). Translocation of plant-N between the various structures has long been acknowledged (e.g. Brenchley and Hall, 1908).

The work by Harper et al. (1987); contrary to the findings of Gregory et al. (1979), demonstrated that a larger proportion of the TN_{grain} was translocated from the leaves than stems but stems contributed slightly more nitrogen obtained from the fertiliser. In post-anthesis, approximately 50% of the TN_{grain} was found to be remobilised from leaves and stems and the remaining 50% directly from the soil supply after anthesis (Harper et al., 1987). It is possible that some of the differences observed in TN_{grain} between the fertilisers, particularly biosolids, were due to SMN following the application of the fertiliser. Following application, available nitrogen is taken-up by the crop and assimilated in stems and leaves to be translocated later to grains. During grain filling, the direct contribution of nitrogen from the soil to the grains is restricted by the availability of soil nitrogen, mainly in biosolids-treated plots and to a lesser extent in OMF-treated plots which necessitate the organic-N in the fertiliser to be mineralised. For this reason, differences in TN_{grain} are augmented compared with the plots treated with urea where nitrogen does not require undergoing such mineralisation process. This observation is consistent with the fact that, in general terms, the value of all indexes increased with the concentration of readily available nitrogen in the fertiliser. As highlighted earlier, urea showed consistently higher nitrogen use efficiencies (A_E, R_N and I_P) than OMF_{15}, OMF_{10} and biosolids granules, particularly in the 2nd wheat crop where the total nitrogen load was lower overall.

Values of recovery reported by Johnston and Poulton (2009) for wheat amended with FYM were in the range of 36% to 45.0% which appeared to be of similar order of magnitude to those shown in **Table 7.5**. In general, the use of biosolids granules resulted in lower nitrogen recoveries (range 21.78-44.47%) compared with the rest of the fertiliser materials applied. These differences were more evident in the 2nd than the 1st wheat crop. It may be argued that the effect of the fertiliser type upon the R_N values encountered in the 1st wheat in Avenue Field were influenced by the nitrogen fertiliser type and application rate used in the first dressing. In addition, larger R_N and I_P values were found for the lower range of nitrogen application rates and tended to decrease as crop yield increased. On the steeper part of the response curve which corresponds to the lower range of nitrogen application rates, R_N for each increment of nitrogen is usually high. As grain yield approaches the maximum, and the curve tends to level off, the recovery starts decreasing.

Similarly, for the I_P index when large quantities of nitrogen fertiliser are applied, the plant does not respond to produce enough leaf area to synthesise sufficient amount of carbohydrate to be translocated to the grain or regardless of the amount of nitrogen applied, the grain filling period is shortened (Johnston and Poulton, 2009).

This was observed in the 1st wheat crop in Avenue Field which received an additional 100 kg [N] ha^{-1} on top of the required fertilisation level for the treatment and yet the I_P values (excluding that of biosolids-treated plots) corresponding to the maximum yields were in the similar range for both crops (33.17-42.88 and 31.72-41.81 kg kg^{-1} for the 1st and 2nd wheat crops respectively). When comparing the 1st and 2nd wheat crops, the values of A_E and I_P calculated for the maximum crop yield, decreased to a lesser extent in Avenue Field than Chippies Field.

A possible explanation is with regards to the rainfall recorded in the spring and early summer (April-July) in both years (200.4 mm in 2008 and 70.6 mm in 2010) which could have restricted nitrogen uptake and consequently crop yield. Overall, grain yield decreased to a larger extent in the 2nd wheat crop in Chippies Field than in Avenue Field which could be due to a number of factors including higher nitrogen rates used in 2006-07 in Avenue Field; hence, residual effect of nitrogen applied, and also coarser soil texture in Chippies Field which could have provided the opportunity for enhanced nitrogen leaching over the winter time. An effect of the crop variety cannot be fully justified since the recommended list given annually by the HGCA (HGCA, 2008) showed that Nijinsky has an overall performance which is slightly above that of Claire, especially on light soils (102% and 100% respectively – as percentage grain yield of control variety). The effect of the soil fertility status (SOM, SMN and extractable-P and -K) on the indexes reported above will be further discussed in **Section 7.3.3** together with the data coming from the soil chemical analyses.

iv. Crop yield components

The various crop yield components measured are presented in **Table 7.6** for the harvest seasons of 2006-07 to 2009-10 and the regression analyses conducted are shown in **Figure 7.9**. During the pilot investigation in Avenue Field (2006-07) four-square samples of the crop were not taken for which the indexes (except W_{1000}) could not be determined for that particular year. The statistical analysis showed that for the 1st wheat crop in Avenue Field (2006-07) there were not significant differences in W_{1000} grains between the control and the treatments ($p>0.05$). The effects of the fertiliser type, the nitrogen application rate and the interaction between the two parameters were also found to be nonsignificant (p-values >0.05). For the 2nd wheat crop in Avenue Field (2007-08), a significant difference ($p=0.011$) in W_{1000} grains was obtained between the control and the treatments (mean W_{1000} grains of 39.70 g and 41.72 g for the control and the treatments respectively; $LSD_{[5\% \text{ level}]}=1.53$), and the same effect was observed for the nitrogen application rate ($p=0.029$); however, there was not a significant effect of the fertiliser type ($p=0.402$).

Table 7.6: Crop yield components measured for winter wheat for the various fertiliser materials used at the experimental plots in Avenue and Chippies Fields and mean values obtained for the period 2006-10 [n=14 except control n=4; *SD*: standard deviation].

Parameter	**Year**					
Harvest index (%)	**2006-07**	**2007-08**	**2008-09**	**2009-10**	**Mean**	***SD***
Control	-	52.20	55.85	46.50	**51.52**	**4.71**
Biosolids	-	56.07	57.39	49.49	**54.32**	**4.23**
OMF$_{10}$	-	56.41	57.79	49.79	**54.66**	**4.28**
OMF$_{15}$	-	56.14	57.29	49.36	**54.26**	**4.29**
Urea	-	56.59	57.44	50.65	**54.89**	**3.70**
Total biomass (kg ha^{-1})	-	-	-	-	-	-
Control	-	6593	15204	4475	**8757**	**5683**
Biosolids	-	11941	17027	7238	**12069**	**4896**
OMF$_{10}$	-	17536	17244	9133	**14638**	**4769**
OMF$_{15}$	-	16151	20416	9760	**15442**	**5363**
Urea	-	17258	20350	10919	**16176**	**4808**
W$_{1000}$ grains (g)	-	-	-	-	-	-
Control	46.51	39.70	43.82	34.74	**41.19**	**5.13**
Biosolids	47.10	41.48	44.69	36.23	**42.38**	**4.70**
OMF$_{10}$	46.40	41.54	46.07	36.58	**42.65**	**4.61**
OMF$_{15}$	46.38	42.22	46.97	39.11	**43.67**	**3.70**
Urea	47.18	41.63	47.11	39.51	**43.86**	**3.89**
Ears per m^{2}	-	-	-	-	-	-
Control	-	355	423	340	**373**	**44.23**
Biosolids	-	447	494	395	**445**	**49.52**
OMF$_{10}$	-	504	488	423	**472**	**42.90**
OMF$_{15}$	-	498	518	419	**478**	**52.35**
Urea	-	505	530	430	**488**	**52.04**

It appears; however, that the differences observed in total biomass with respect to the fertiliser type and the nitrogen application rate were not always reflected on the values of harvest index; since, as highlighted earlier, the effects of these two parameters were found to be nonsignificant ($p>0.05$). This means that the changes occurred in the total biomass as a result of the fertiliser type and/or the nitrogen application rate used were, to some extent, corresponded with changes in grain yield so that harvest indexes were not significantly affected.

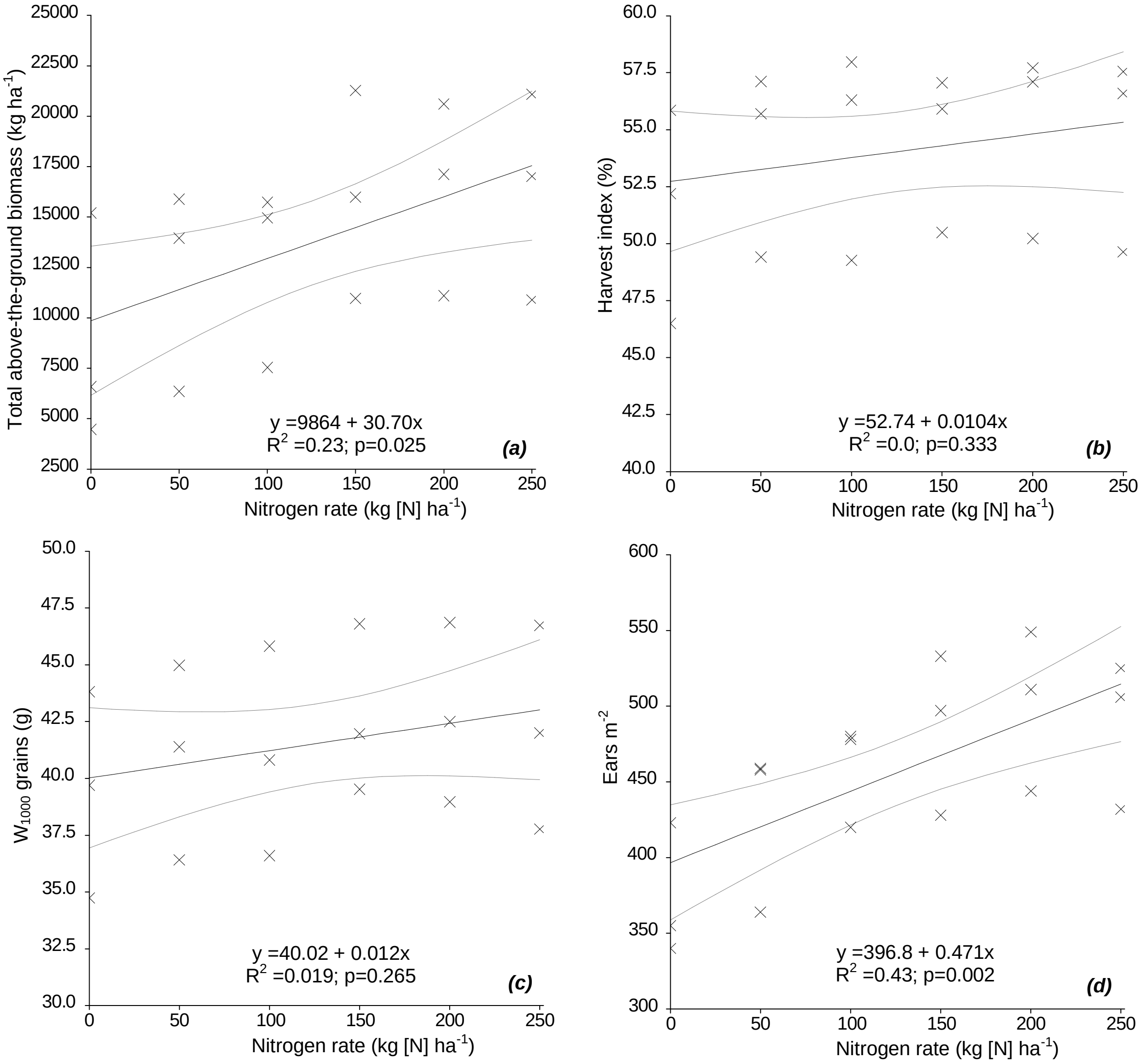


Figure 7.9: Relationship between the various yield components measured in the field experiment and the nitrogen application rates; (*a*) total above-the-ground biomass, (*b*) harvest index (the ratio grain yield to total-above-the ground biomass in percentage), (*c*) weight of [1000] grains, and (*d*) number of ears per square meter. The two curves on both sides of the fitted line represent its 95% confidence interval. Mean values across the whole experiment [n=12 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=8].

The increase in TN_{grain} with the nitrogen application rate reported earlier (**Figure 7.8**), and also the relationship between total-above-the ground biomass with nitrogen application rate highlights the growth dependence from nitrogen supply to the crop (Cordovil et al., 2007).

It also reflects the fact that the efficiency at which the biomass was converted into grain and the translocation of photo-assimilates from vegetative parts on to the grains was also not significantly affected as a result of the changes in total biomass.

When harvest index was regressed against nitrogen rate, the relationship was found to be nonsignificant. However, if the harvest indexes encountered for 2009-10 (dry year) are removed from the dataset (**Appendix A.7.6**) the relationship becomes significant ($p=0.045$). In general, the W_{1000} grains tended to increase with the nitrogen application rate but a consistent (linear) relationship was not observed. The maximum W_{1000} grains value (42.5 g) was obtained at a nitrogen rate equivalent to 200 kg [N] ha^{-1}.

Similarly, in Chippies Field, significant differences between the control and the treatments were observed in both the 1st and the 2nd wheat crops (p-values of 0.019 and 0.017 respectively). Unlike Avenue Field, there was a significant effect of the nitrogen application rate and the fertiliser type on the W_{1000} grains (p-values <0.05). Urea-treated plots resulted consistently in higher W_{1000} grains than the rest of the fertiliser materials. For the 1st wheat crop in Chippies Field, the maximum W_{1000} grains occurred at a rate of 200 kg [N] ha^{-1} (46.86 g); whereas, for the 2nd crop it was at 150 kg [N] ha^{-1} but it showed no statistical difference with that obtained at 200 kg [N] ha^{-1} (39.52 g and 38.97 g respectively; $LSD_{[5\% \text{ level}]}=1.74$).

With regards to harvest index, significant differences were only found for comparisons between the control and the treatments (p-values <0.05) and that was observed across all years. The effect of the nitrogen application rate, the fertiliser type and the interaction between the two factors was nonsignificant (p-values >0.05). There appeared to be an indication that the maximum harvest index was achieved at a nitrogen rate of 200 kg [N] ha^{-1} and that urea consistently showed slightly higher values of harvest index than the rest of the fertiliser materials used, as shown also in **Table 7.6**.

The statistical analysis of the data corresponding to total biomass showed a similar pattern to that reported for the W_{1000} grains and harvest index across all years. Significant differences in total biomass were found between the control and the treatments (p-values <0.05) which was consistent with the results obtained for harvest index and grain yield for all years. However, and unlike the results obtained for harvest index, significant differences in total biomass were found with respect to the fertiliser type (p-values <0.001) and the nitrogen application rates ($p<0.05$) for all years. In general, total biomass was found to be significantly higher in urea-treated plots compared with the rest of the fertiliser materials which was also consistent with the overall larger grain yields obtained in those plots. In addition, as reported earlier for W_{1000} grains and harvest index, the highest biomass was always measured when nitrogen was applied at a rate equivalent to 200 kg [N] ha^{-1}.

This indicated that harvest indexes were negatively affected by water deficits occurred in late spring in 2010 and that the effect was more evident as the nitrogen rate was increased. The overall effect responded to a decline in grain yield; in fact, grain yield is a function of the transpiration rate which is restricted under drought stress (Acevedo, 1987; Richards, 1987; Acevedo et al., 2002). Harvest index is ultimately determined by the amount of water transpired during grain filling and the prevailing transpiration efficiency around this period (Passioura, 1977; Acevedo et al., 2002).

The number of ears per m^2 showed significant differences between the control and the treated plots for all years (p-values <0.05). In Avenue Field (2007-08), ears per m^2 was not significantly affected by the fertiliser type (p=0.099), the nitrogen application rate (p=0.361) or the interaction between the two factors (p=0.914). Since the effect of the fertiliser type on the weight of the grains was nonsignificant, differences in grain yield may only be explained by differences in the number of grains per ear. It is possible that increased above-the-ground biomass production in urea-treated plots, compared with the rest of the fertiliser materials used, has contributed to sustain a larger number of kernels per ear for an already defined number of ears per m^2 which helps to explain the increased grain yield obtained overall in urea-treated plots. In Chippies Field, the effect of the fertiliser type on the number of ears per m^2 was only observed in the 1st wheat crop (p=0.007) but the effect of the nitrogen rate was observed in both years (p-values <0.001 and 0.021 respectively).

In agreement with the results obtained for other crop yield components measured, the use of urea consistently showed a higher number of ears per m^2 compared with the rest of the fertiliser materials used. In addition, with respect to the nitrogen application rate, the number of ears per m^2 was found to be consistently higher at 200 kg [N] ha^{-1} across all years.

7.3.2 Rye grass – dry matter yield

As highlighted in **Section 7.2.1**, rye grass was introduced in Avenue Field after the 2nd wheat crop and it was maintained during the following two years (2009 & 2010). The plots received exactly the same treatments in terms of fertiliser type and nitrogen application rates to those used in the previous years with winter wheat. In this section, the emphasis is on the annual yield of rye grass and its response to applied fertiliser. The data corresponding to individual cuts is reported in **Appendix A.7.7**. Grass yield and comparison of responses between years were difficult to make; firstly, because the meteorological conditions observed each year differed markedly.

Secondly, because the application of fertiliser in 2010 was conducted after the first cut was performed for which total grass yield was affected by management practices including the ploughing up of the soil during the seedbed preparation in year one and also the timing of fertiliser application both years. In addition, since the fertilisers were applied as single dressings regardless of the nitrogen rates, it was reasonable to analyse the annual yield data instead of individual cuts. In practice, however, nitrogen is usually applied throughout the growing season (up to 4-5 times) depending on the purpose of the grass sward and the total nitrogen rate (MAFF, 2000).

Following the establishment of the grass, fertiliser was applied to all plots on 10th June 2009 and the first cut was performed on 14th July 2009 which gave approximately 60 days from establishment to first cut. The second and third cuts were conducted on 25th August 2009 and 21st October 2009 respectively. In 2010, the first cut was conducted on 17th April 2010; as highlighted above, prior to the fertiliser application which was done on 18th April 2010. The second cut was done on 20th June 2010 which also gave approximately 60 days between the two cuts. Sparrow (1979) applied a number of different models to describe the response curves of grass to nitrogen which included quadratic polynomial, split-line, modified inverse linear (Greenwood et al., 1971), exponential (Reid, 1978) and inverse quadratic (Nelder, 1966). In most cases, however, the grass' response to nitrogen has a linear component followed by a section where yield either remains constant or starts decreasing (Sparrow, 1979). In particular, the work undertaken by Sparrow (1979), and later Morrison et al. (1980), suggested that the inverse quadratic response curve accounted for more variability on average and was more acceptable biologically than the other models used. The authors reported that this type of response was found to produce the least residual mean square indicating that the model represented the response reasonably well. It is important to note that the results of these works were based on large experiments which also included a significantly greater range of nitrogen application rates than those used in Avenue Field.

The responses of rye grass to nitrogen were described by quadratic functions which were shown to have acceptable fits. In addition, the terms derived from the equations appeared to have produced reasonable solutions. It is also important to note that linear relationships are also possible since the estimates of parameters were significant for the linear terms in all cases. In this respect, the response to the application of biosolids did not result in the square term being significant ($t_{pr}>0.05$) for which its response can also be explained by a linear function. Similar observations were made for biosolids (and also OMFs) in the second wheat crops.

The studies of Sparrow (1979) and Morrison et al. (1980) had also shown that typical responses of grass to nitrogen application rates in the range of 0 to 300 kg [N] ha^{-1} were found to be linear. However, since the coefficients of the square term were negative there was an indication that yields started to decline above certain level of nitrogen fertilisation under the prevailing experimental conditions. For this reason, the use quadratic functions to describe the response curves may be justified which also permitted the derivation of Y_{max} and Y_{10} as indicated below. Morrison et al. (1980) highlighted that leaching losses of fertiliser-N from grass are unlikely to be of significance until the quantity of fertiliser-N applied is excessive in terms of yield response. Such rate of N would not be economically justified and the authors suggested that a critical rate would be equivalent to a rate of fertiliser-N about the N_{10}. On this basis, the optimum yield (Y_{10}) can be inferred from the yield to nitrogen response curves. As highlighted earlier, the use of quadratic functions provides more satisfactory biological responses compared with other models used (Morrison et al., 1980). Based on the work of Morrison et al. (1980), the work conducted in Avenue Field investigated the following parameters which were derived from quadratic response curves:

- $Y_{\max}$: the maximum yield of grass; $Y_{\max}\left(\frac{dy}{dx}=0\right)$ in kg [DM] ha^{-1};
- Y_{10} : the optimum yield of grass; defined as the yield at which the response is equivalent to 10 kg [DM] per kg [N] added; $Y_{10}\left(\frac{dy}{dx}=10\right)$ in kg [DM] ha^{-1};
- $N_{\max}$: nitrogen application rate required for $Y_{\max}$; in kg [N] ha^{-1};
- N_{10} : nitrogen application rate required for Y_{10} ; in kg [N] ha^{-1}; and
- Mean annual dry matter yield; $\overline{Y}$ (kg [DM] ha^{-1} y^{-1}).

The general form of the response curve is represented by:

$$y = a + bx - cx^2 \tag{7.1}$$

Where: $'a','b', and\ \ 'c'$ are the regression coefficients, $'y'$ is the yield of the grass, and $'x'$ is the rate of nitrogen applied to the grass crop. The equation is then derived in the form shown earlier in **Chapter 2**. The responses of rye grass to applied fertiliser and biosolids are shown in **Figures 7.10** and **7.11** for 2009 (3 cuts) and 2010 (2 cuts) respectively. The analysis of variance showed that there were significant differences in the annual yield of the grass in 2009 between the control and the treatments (p<0.001). There were also significant differences with respect to the fertiliser type and the nitrogen application rate (p-values <0.001).

However, the interaction between the fertiliser type and the nitrogen application rate was found to be nonsignificant (p=0.764). Overall, the application of fertiliser increased the production of dry matter by *c.*80% compared with the unfertilised controls (mean values of 6188 and 11186 kg [DM] ha^{-1}; $LSD_{[5\% \text{ level}]}$ =976.9 for the control and the treatments respectively). In general, the yield of the grass in 2009 was found to increase with concentration of nitrogen in the fertiliser and in particular with the concentration of readily available nitrogen. Yield also increased with the nitrogen application rate and there was a significant correlation (p-values <0.001) between the nitrogen rate and the yield of the grass as shown in **Figure 7.10.**

A similar pattern to that observed in 2009 was found in 2010 despite that the statistical analysis included two cuts only. Significant differences were found between the control and the treatments (p<0.001). The application of fertiliser increased the overall production of dry matter by approximately three times compared with the unfertilised controls (mean values of 2192 and 6690 kg [DM] ha^{-1}; $LSD_{[5\% \text{ level}]}$ =823.0 for the control and the treatments respectively). There were also significant differences in production of dry matter with respect to the fertiliser type and the nitrogen application rate (p-values <0.001) which was also correlated with grass yield (p-values <0.001). The interaction between the two factors however did not result in a significant effect (p=0.739). When comparing the first and the second cuts in 2009 and 2010, a much marked increase (*c.*7.5 times larger) in dry matter was observed overall for fertilised plots between the first and the second cuts in 2010. For the first cut in 2010; however, all treatments produced similar levels of dry matter (**Appendix A.7.7**). This was also an indication that the residual effect of fertiliser applied in the previous years had a negligible effect upon the yield of the grass. The main parameters derived from the response curves obtained for the grass in 2009 and 2010 are shown in **Tables 7.7a-b** respectively. The mean yield ($\overline{Y}$) values shown correspond to the yield of the grass obtained for the specified fertiliser type across the whole experiment; it has been calculated for the entire range of nitrogen application rates used. The calculated Y_{max} are equivalent to the potential harvestable yield given the climatic and soil conditions and subjected to the particular crop management practices (Morrison et al., 1980). The calculated values of Y_{max} for Avenue Field were in a similar range to those reported by Morrison et al. (1980) for more than 20 sites across England and Wales (ranging between 6.51 and 15.04 t [DM] ha^{-1} y^{-1}). The Y_{max} obtained for 2010 were still in the range despite including only two cuts. The value of Y_{10} and the ratio Y_{10}:Y_{max} encountered for Avenue Field were also of the same order of magnitude to those indicated in the work above-mentioned and they were found to be $\overline{Y}_{10} \approx 10.90$ t [DM] ha^{-1} y^{-1} and $\overline{Y}_{10} \approx 0.80 - 0.95 * Y_{\max}$.

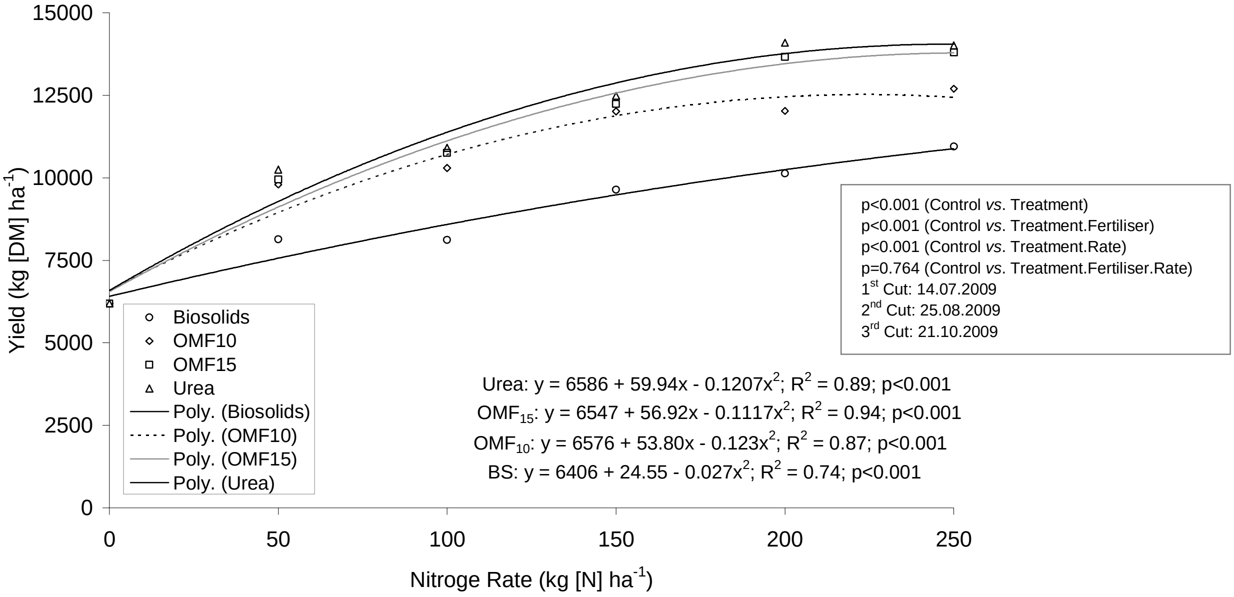


Figure 7.10: Relationship between nitrogen application rate and annual yield of rye-grass in Avenue Field harvested over three cuts in 2009 (14th July, 25th August, and 21st October respectively) following application of biosolids granules, OMF_{10}, OMF_{15} and urea to the grass crop [$LSD_{[5\% \text{ level}]}$ =1648.4 (min.rep); $LSD_{[5\% \text{ level}]}$ =1504.8 (max-min. rep); $LSD_{[5\% \text{ level}]}$ =1345.9 (max.rep); n=3 except controls n=4, and plots treated with 250 (kg [N] ha^{-1} n=2].

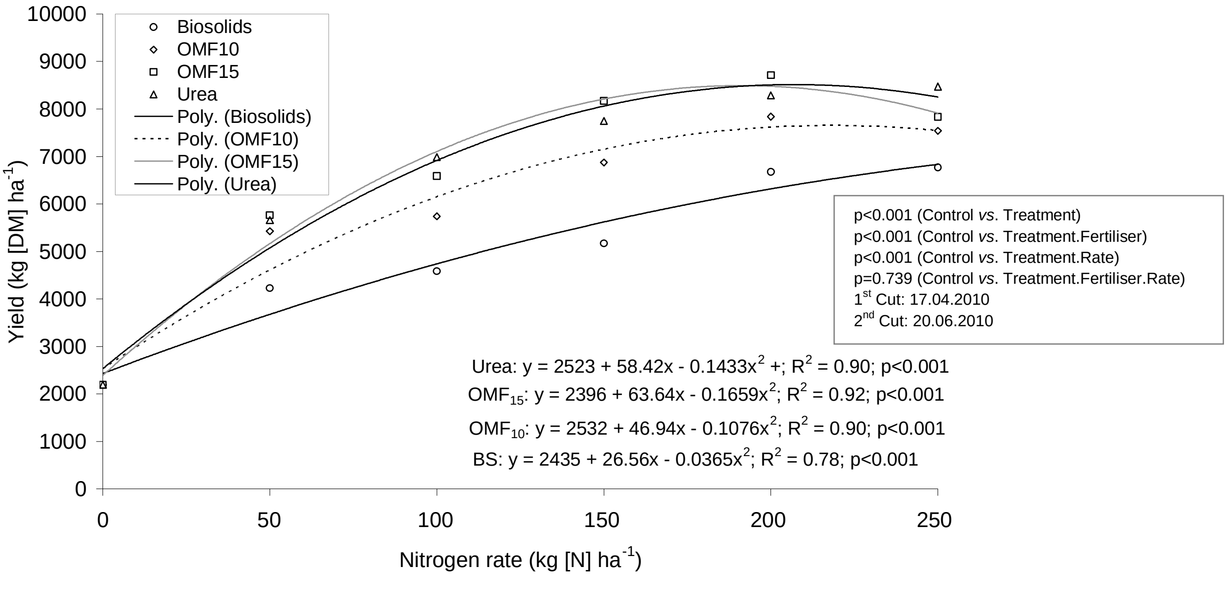


Figure 7.11: Relationship between nitrogen application rate and annual yield of rye-grass in Avenue Field harvested over two cuts in 2010 (17th April and 20th June) following application of biosolids granules, OMF_{10}, OMF_{15} and urea to the grass crop [$LSD_{[5\% \text{ level}]}$ =1388.8 (min.rep); $LSD_{[5\% \text{ level}]}$ =1267.8 (max-min. rep); $LSD_{[5\% \text{ level}]}$ =1133.9 (max.rep); n=3 except controls n=4, and plots treated with 250 (kg [N] ha^{-1} n=2].

It is important to note that the values of N_{max} (**Tables 7.7a-b**) that are well above the maximum level of nitrogen fertilisation used in the field studies (i.e. 250 kg [N] ha^{-1}) should be treated with caution. These are based on the yield to nitrogen response curves and they resulted from an extrapolation of the data that falls outside the range of nitrogen application rates used.

Table 7.7a: Parameters derived from the response curves of rye grass to nitrogen for Avenue Field as shown in Figure 7.10 for 2009. Grass yield and nitrogen application rate expressed in kg [DM] ha^{-1} and kg [N] ha^{-1} respectively [For comparisons between $\overline{Y}$ use: LSD$_{[5\% \text{ level}]}$ =1048.7 (max-min. rep); LSD$_{[5\% \text{ level}]}$ =623.0 (max.rep); n=14 except control n=4].

	---------- 2009 ----------						
Treatment	$\overline{Y}$	Y_{max}	N_{max}	Y_{10}	N_{10}	Y_{10}:Y_{max}	N_{10}:N_{max}
Control	6188	-	-	-	-	-	-
Biosolids	9285	11986	454.6	11060	269.4	0.92	0.59
OMF_{10}	11270	12459	218.7	12255	178.1	0.98	0.81
OMF_{15}	11958	13798	254.8	13574	210.1	0.98	0.82
Urea	12230	14027	248.3	13820	206.9	0.99	0.83

Table 7.7b: Parameters derived from the response curves of rye grass to nitrogen for Avenue Field as shown in Figure 7.11 for 2010. Grass yield and nitrogen rate expressed in kg [DM] ha^{-1} and kg [N] ha^{-1} respectively [For comparisons between $\overline{Y}$ use: LSD$_{[5\% \text{ level}]}$ =883.6 (max-min. rep); LSD$_{[5\% \text{ level}]}$ =524.9 (max.rep); n=14 except control n=4].

	---------- 2010 ----------						
Treatment	$\overline{Y}$	Y_{max}	N_{max}	Y_{10}	N_{10}	Y_{10}:Y_{max}	N_{10}:N_{max}
Control	2192	-	-	-	-	-	-
Biosolids	5394	7266	363.9	6581	226.8	0.91	0.62
OMF_{10}	6624	7651	218.1	7418	171.7	0.97	0.79
OMF_{15}	7385	8499	191.8	8348	161.7	0.97	0.84
Urea	7357	8477	203.8	8302	168.9	0.98	0.83

The work undertaken by Morrison et al. (1980) concluded that the mean response curve to applied nitrogen and its derived variates were highly influenced by particular (local) conditions of soil and climate and that the main factor affecting yield, Y_{max} and Y_{10}, was soil-water availability. It appeared that in 2010, the annual mean yield in OMF_{15}-treated plots marginally outperformed urea-treated plots despite the differences between the two fertilisers were not significant according to the calculated LSD$_{[5\% \text{ level}]}$ values previously shown.

The same was observed for the variates derived as less nitrogen was required for both maximum and optimum yields respectively. This could be attributable to the particular meteorological conditions in 2010, especially rainfall during the early spring as only 8.2 mm were recorded in April 2010 (Met Office, 2010). The occurrence of soil water shortages in the upper 100-150 mm of the soil profile have been shown to impede the availability of nitrogen to the grass crop (Garwood and Williams, 1967). In addition, grass yield in OMF- and biosolids-treated plots could have benefitted from a slower release nitrogen source that would mineralise progressively given adequate soil-water and temperature conditions later in the season thereby matching crop nitrogen uptake.

The work conducted by Anslow and Green (1967) showed that seasonal growth of perennial rye grass, measured as kg [DM] ha^{-1} day^{-1}, is characterised by a peak in May follow by a decline in the rate of accumulation of DM in June, and by a second but smaller peak in July. The application of fertiliser, especially in 2009, did not exactly match the maximum rate of growth and it should have been made instead approximately 30-40 days earlier. Equally, an anticipated 2nd cut in 2010, by approximately 20 days, could have resulted in overall higher dry matter yields by matching the cut with the end of the maximum growth rate. A delay in this 2nd cut in 2010 is understood to have provided the opportunity for mineralisation of the organic OMF- and biosolids-N fractions to progress to a further extent (helped also by wetter conditions during August) thereby narrowing the differences in dry matter yield with respect to urea-treated crop.

With regards to the N_{max} values encountered, they appeared to be considerably lower than those reported by Morrison et al. (1980) which were in the range of 500 to 700 kg [N] ha^{-1} on average for most of the sites investigated. However, the same study indicated that a number of sites across England and Wales were found to have N_{10} values in the range of 183 to 299 kg [N] ha^{-1} which appear to be in much closer agreement to those encountered for Avenue Field. The difference with these values strives in the type of response curves fitted to the data and the way the associated terms were derived from the functions. Except for biosolids, the N_{max} values estimated for Avenue Field were often lower than the recommended rates (>250 kg [N] ha^{-1}; excluding grass for hay production) given in RB209 (MAFF, 2000). The N_{10} values showed in **Tables 7.7a-b** indicate the nitrogen rates above which a further increase in nitrogen would result in a yield response of less than 10 kg [DM] ha^{-1} and it has been reported to be an adequate lower limit of response from the grass management perspective (Morrison et al., 1980). As can be seen from the tables, on average for both OMF products, an input of $0.82*N_{max}$ yielded $0.98*Y_{max}$ which was similar to that of urea ($0.83*N_{max}$ yielded $0.99*Y_{max}$).

For biosolids, a yield of 0.92*Y_{max} required an input of 0.61*N_{max} but yield was considerably lower (**Tables 7.7a-b**). The choice of a particular fertiliser type may be made on the basis of crop yield using the mean yield of the grass crop ($\overline{Y}$) as reference for comparisons. In this regard, the differential mean yields ($\Delta\overline{Y}$), taking as reference level the $\overline{Y}$ of biosolids, were calculated and they are shown in **Table 7.8** for the two years of grass. The mean yield for 2009 and 2010 for each treatment could not be calculated as only two cuts were conducted in the second year.

Table 7.8: Differential mean yield ($\Delta\overline{Y}$; kg [DM] ha^{-1}) and relative yield (% $\overline{Y}$ of biosolids-treated plots) for rye grass in 2009 & 2010.

Treatment/	Biosolids		OMF_{10}		OMF_{15}		Urea	
Year	$\overline{Y}$	%	$\Delta\overline{Y}$	%	$\Delta\overline{Y}$	%	$\Delta\overline{Y}$	%
2009	9285	100	1985	121.4	2673	128.8	2945	131.7
2010	5394	100	1230	122.8	1991	136.9	1963	136.4

Grass nitrogen yield and recovery of fertiliser nitrogen could not be estimated with the data available from the field experiments since analyses of TN_{plant} were not conducted. However, this was discussed in **Chapter 6** with the data obtained in the glasshouse studies which serve as reference values.

7.3.3 Soil analyses

i. Total soil nitrogen

The mean values of total soil nitrogen (TN_{soil}) prior to the start of the experiment were reported in **Table 7.2** for Avenue and Chippies Fields respectively. In Avenue Field, soil analyses were subsequently performed in post-harvest of wheat in 2008 and following the 2nd cut of grass in 2010. A statistical analysis was first undertaken to identify changes occurred in TN_{soil} over time. This was done by comparing the initial values in the soil prior to the start of the experiments against those obtained in post-harvest of wheat in 2008 and after the 2nd cut of grass in 2010 respectively. This first analysis did not show a significant difference in TN_{soil} between the control and the treatments ($p=0.121$) for which it was suspected that there was an important effect of the crop, following the introduction of grass in the rotation, upon the values of TN_{soil} encountered. Therefore, the statistical analysis was then repeated to compare the initial values at the start of the experiment with those obtained in post-harvest of wheat in 2008 only. Subsequently, these values were compared with those obtained in 2010 which corresponded to the end of the experiment; i.e. after the 2nd cut of grass in 2010.

In post-harvest of wheat, the unfertilised controls were found to be significantly different from the treated plots (p=0.006). Overall, the application of fertiliser increased TN_{soil} levels with respect to the control which is thought to have been favoured by the first nitrogen dressing with UAN (33% N) in the spring of 2007. Also, the differences between the control and treated plots were augmented as a result of the decrease in the TN_{soil} observed in the control plots in post-harvest of wheat in 2008 with respect to the initial level (mean values of 0.148 and 0.149% (w w^{-1}) respectively; $LSD_{[5\% \text{ level}]}$ =0.0036). For the control plots, nitrogen off-take in the grain and the absence of fertiliser applications enhanced this process. In addition, significant differences in TN_{soil} were encountered with respect to the fertiliser type (p=0.001), the nitrogen application rate (p=0.002) and the interaction between two factors (p=0.012). The largest increase in TN_{soil} was recorded on biosolids-treated plots which responded to the fact that biosolids-N is almost entirely organic-N. It is also possible that the excess biosolids-N applied in 2007 (above the rate specified by the treatment) had contributed to this effect.

The use of OMF_{10} and OMF_{15} resulted in intermediate levels of increase in TN_{soil} between those found for biosolids- and urea-treated plots. When comparing TN_{soil} in post-harvest of wheat in 2008 with that at the end of the experiment in 2010, the control plots did not exhibit, overall, significant differences with respect to the treatments (p=0.124) which could be attributable to the increase in TN_{soil} recorded in control plots following two years of grass. In this respect, TN_{soil} in the control plots increased from 0.148 to 0.164 % (w w^{-1}) [$LSD_{[5\% \text{ level}]}$ =0.013]. Hence, TN_{soil} levels for the control plots were restored, even, above the initial level recorded at the start of the experiment in 2007. This increase can be partially attributed to the fact that there was not a complete removal of plant material from the plots following the harvest of the grass. Also, limited growth in unfertilised crop prevented nitrogen levels in the soil from running down. During the years under wheat, only the straw was returned back to the soil whereas during the two years under grass, after taking the four-square sample for determination of DM, a topper was passed over the plots but leaving the plant material cut on the soil which could have contributed to maintain/increase TN_{soil} levels.

As reported for the two years under wheat, a significant effect was also found for the fertiliser type ($p<0.001$) and the nitrogen application rate (p=0.008) but there was not interaction between the two factors (p=0.133). The changes in TN_{soil} observed in Avenue Field are shown in **Figures 7.12-7.13**.

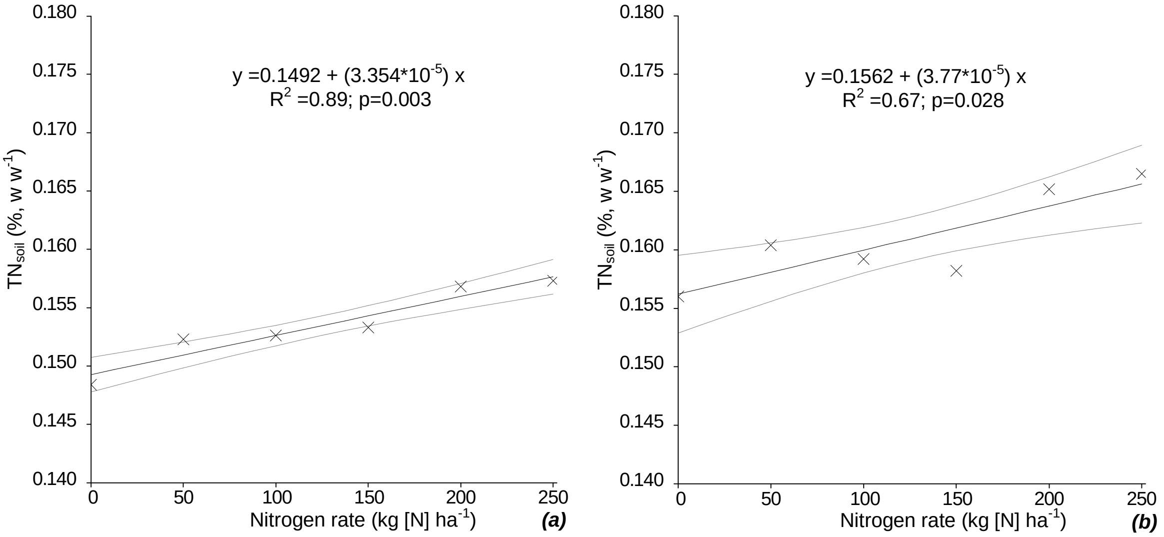
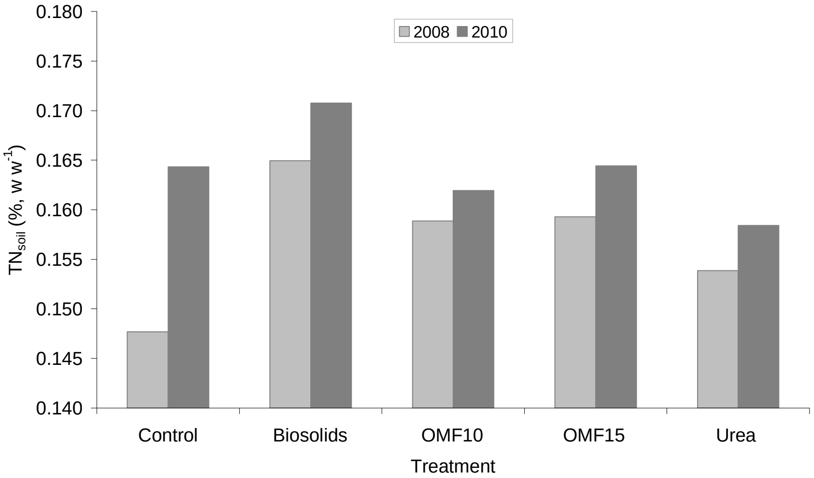


Figure 7.12: Relationship between nitrogen application rate and TN_{soil} for Avenue Field; *(a)* in post-harvest of the 2nd wheat crop [$LSD_{[5\%\ level]}$ =0.004 (max-min. rep); $LSD_{[5\%\ level]}$ =0.003 (max.rep)], and *(b)* at the end of the experiment in 2010 [$LSD_{[5\%\ level]}$ =0.008 (max-min. rep); $LSD_{[5\%\ level]}$ =0.005 (max.rep)]. Mean values across the whole experiment [n=12 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=8]. The two curves on both sides of the fitted lines represent its 95% confidence interval.



Initial level (Avenue Field, 2007): 0.149 (%, w w^{-1})

Figure 7.13: Mean TN_{soil} levels recorded in Avenue Field for the control and the treated plots in post-harvest of the 2nd wheat in 2008 and at the end of the experiment in 2010 [$LSD_{[5\%\ level]}$ =0.01 (max-min. rep); $LSD_{[5\%\ level]}$ =0.006 (max.rep); p=0.911; n=14 except control n=4].

By analysing the complete dataset; i.e. initial TN_{soil} levels, post-harvest of wheat 2008, and levels at the end of experiment in 2010, it can be seen that there was a significant effect of the fertiliser type with respect to the time (p=0.03).

TN_{soil} levels were increased to a larger extent in biosolids-treated plots than the rest of the treatments (mean TN_{soil} values at the end of the period were 0.164, 0.171, 0.162, 0.164, and 0.158% (w w^{-1}) for the control, biosolids-, OMF_{10}-, OMF_{15}- and urea-treated plots respectively; $LSD_{[5\% \text{ level}]}$ =0.0087 and 0.0052 for comparisons between the control and the treatments and between the treatments respectively). The lower value of TN_{soil} recorded on urea-treated plots could be the case of increased nitrogen content in plant material, including TN_{grain}, as well as higher crop yield. Since an increased amount of nitrogen was withdrawn from the soil to sustain a larger crop yield then a smaller value in the soil was recorded in the analysis. It also is important to take account of the timing of sampling in 2010; as this was conducted in July with the grass crop growing actively (Anslow and Green, 1967), it is expected that much nitrogen has been taken-up from the soil and hence not detected in the soil analysis. There is also a possibility for the excess nitrogen (mostly mineral) to be leached down below the depth of sampling (>0.2 m) resulting in lower values of TN_{soil} measured in the analysis but it appears to be quite unlikely as there were only 36.2 mm of rain recorded for June and July 2010 (Met. Office, 2010). High evapotranspiration rates at this time of the year would drive soil water and nitrogen in solution close to the root-zone for which this possibility should be discarded. In the first case; i.e. enhanced N content in plant, effectively leads to increased NUE, as recorded earlier for urea-treated plots in winter wheat. However, this cannot be fully supported with the data available for this experiment.

In Chippies Field, comparisons were made for TN_{soil} levels in post-harvest of wheat in 2010 and the initial level in the soil at the start of the experiment in March 2009, recorded prior to the application of fertiliser. Similar to the observations made for Avenue Field following the 2^{nd} wheat crop, in Chippies Field, significant differences in TN_{soil} were found between the initial level and the levels in post-harvest of wheat ($p=0.006$). Overall, the application of fertiliser increased TN_{soil} by *c.*8.5% with respect to the unfertilised control. There was also a significant effect of the nitrogen application rate on the TN_{soil} values recorded in 2010 ($p<0.001$). However, no significant differences were found with respect to the fertiliser type used ($p=0.739$) or the interaction between the nitrogen application rate and the fertiliser type ($p=0.262$) which are a distinctive feature from Avenue Field. Although the differences were not statistically significant ($p>0.05$), biosolids-treated plots still showed the largest increase in TN_{soil} with respect to the unfertilised control plots (mean TN_{soil} values were 0.127, 0.139, 0.1361, 0.138 and 0.139% (w w^{-1}) for the control, biosolids-, OMF_{10}-, OMF_{15}- and urea-treated plots respectively; $LSD_{[5\% \text{ level}]}$ =0.008 and 0.005 for comparisons between the treatments and control, and between the treatments respectively).

In addition, after two consecutive wheat crops, TN_{soil} for control plots did not change significantly (p=0.060) which was not the case for Avenue Field between 2006-07 and 2007-08. The changes in TN_{soil} recorded for Chippies Field are shown in **Figures 7.14-7.15**.

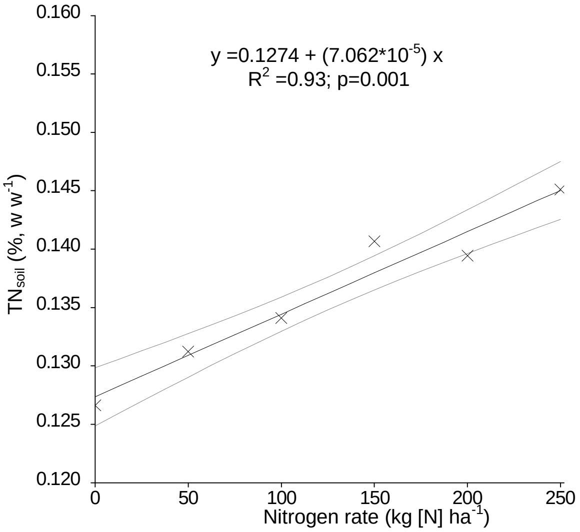


Figure 7.14: Relationship between nitrogen application rate and TN_{soil} for Chippies Field in post-harvest of the 2nd wheat crop in 2010 [$LSD_{[5\%\ level]}$ =0.0084 (max-min. rep); $LSD_{[5\%\ level]}$ =0.0053 (max.rep)]. Mean values across the whole experiment [n=12 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=8]. The 95% confidence interval of the fitted line is represented by the curves on both sides of the line.

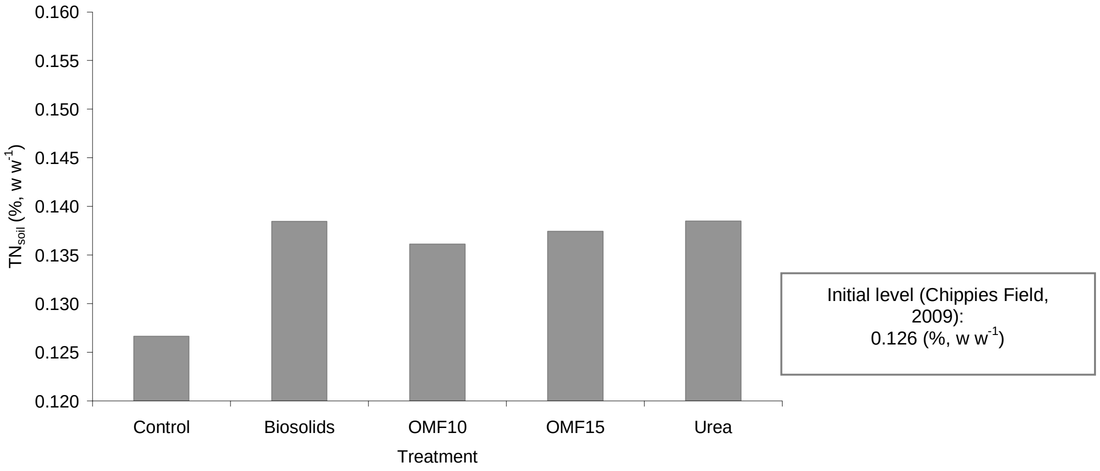


Figure 7.15: Mean TN_{soil} levels recorded for the control plots and the treatments in post-harvest of the 2nd wheat crop in Chippies Field in 2010 [$LSD_{[5\%\ level]}$ =0.008 (max-min. rep); $LSD_{[5\%\ level]}$ =0.005 (max.rep); p=0.739; n=14 except control n=4].

ii. Soil mineral nitrogen

Soil mineral nitrogen (SMN) was determined every year prior to the fertiliser application and at/around harvest of wheat and following the last cut of the grass. Unfortunately, soil sampling was not conducted after the 1st wheat crop in Avenue Field in 2007 which could have provided a valuable indication of residual SMN in post-harvest as a result of the large nitrogen application rates used that particular year. The changes in SMN recorded for Avenue Field are shown in **Figure 7.16** and the relationship between SMN and the nitrogen application rate is shown in **Figure 7.17**. The statistical analysis of the data for Avenue Field showed that, overall, there were not significant differences in SMN between the control and the treated plots ($p=0.714$) and the same was observed with regards to the fertiliser type ($p=0.309$), the nitrogen application rate ($p=0.258$) and the interaction between the two factors ($p=0.932$). When factoring in the time, a significant effect was observed ($p<0.001$) which indicates that SMN levels in post-harvest were significantly different between the sampling events. To certain extent, this may be explained by the timing of sampling in relation to nitrogen uptake by the crop and also in relation to the weather conditions; i.e. rainfall and temperature, recorded between the peak of nitrogen uptake by the crop and the time of sampling. A significantly higher SMN level, equivalent to 4.28 mg [N] kg^{-1}, was found in post-harvest of wheat in 2008 compared with the levels recorded during the grass years following the 3rd and 2nd cuts in 2009 and 2010 respectively (mean values of SMN across the whole experiment equivalent to 2.48 and 0.81 mg [N] kg^{-1} for 2009 and 2010 respectively). The lower values measured overall in grass respond to the fact that nitrogen uptake continued in the autumn which, effectively, reduced the amount of SMN determined in the analysis. There is also scope for nitrogen leaching as the rate of growth by the crop slows down and rainfall increases in the autumn.

By contrast, a relatively low value of SMN (0.82 mg [N] kg^{-1}) was recorded after the 2nd cut in 2010 as crop growth and therefore nitrogen uptake was still high at this time of the year. For the wheat crop, the sampling was conducted more than 60 days after the peak of nitrogen uptake which occurs around anthesis (Harper et al., 1987). During this 60 days period, which also coincides with relatively low precipitation and moderate temperatures, (mineral) nitrogen levels can be partially restored. Residual SMN in post-harvest of wheat can potentially be used in the following crop in the rotation; e.g. oilseed rape especially for early sown crops, and should be accounted for if nitrogen is to be applied in the autumn. Overall, and across the whole experiment, a total of *c.*4.3 mg [N] kg^{-1} [soil] where found in post-harvest of wheat in 2008 which, to a depth of 0.2 m, are equivalent to *c.*11.5 kg [N] ha^{-1}.

The amount indicated above appears to be important and it can potentially be deducted from nitrogen applications needed for example in establishment of oilseed rape (soils with SNS ≤2).

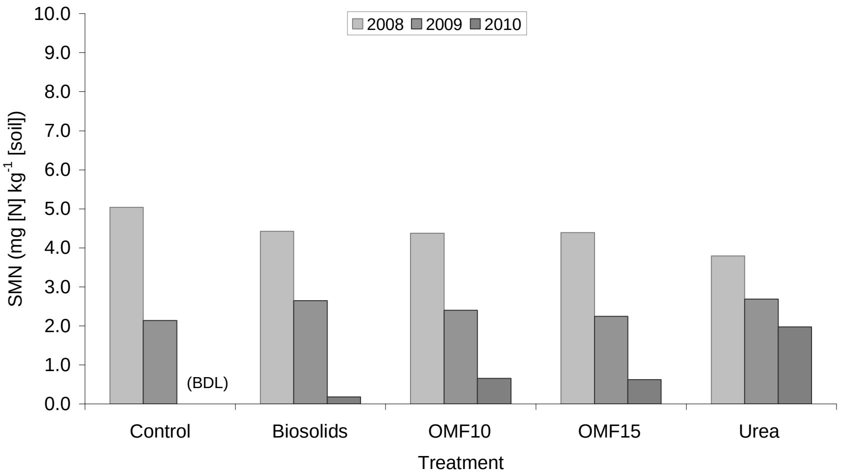


Figure 7.16: Mean SMN recorded for the control plots and the treatments in Avenue Field in post-harvest of the 2nd wheat crop (2008), and following the 3rd and 2nd cuts of the grass in 2009 and 2010 respectively [LSD$_{[5\%\ level]}$ =1.738 (min.rep); LSD$_{[5\%\ level]}$ =1.354 (max-min. rep); LSD$_{[5\%\ level]}$ =0.805 (max.rep); p=0.002; n=14 except control n=4]. BDL: below detection limit.

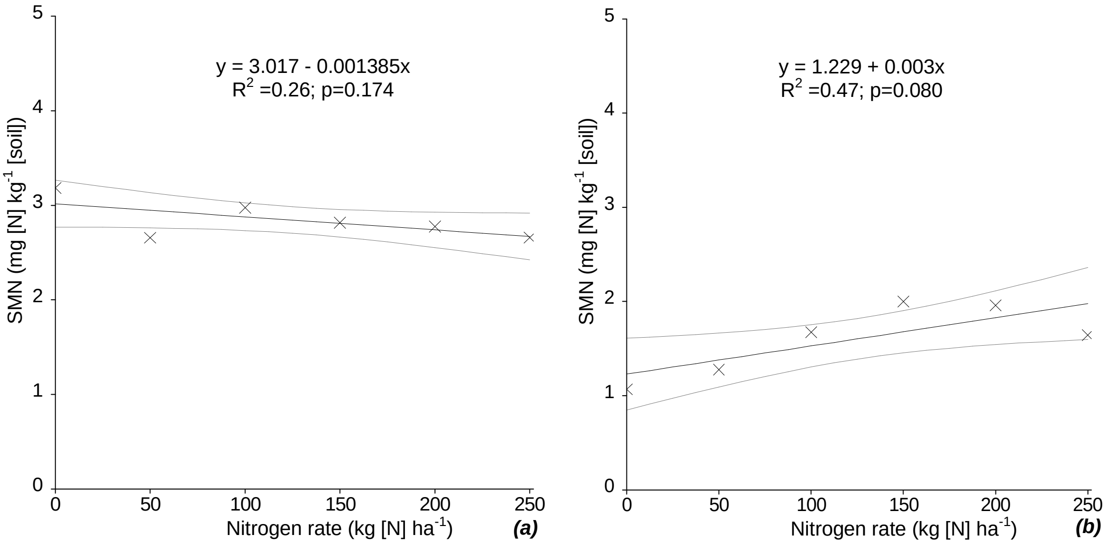


Figure 7.17: Relationship between nitrogen application rate and SMN for Avenue Field; (*a*) post-harvest of the 2nd wheat crop in 2008 [LSD$_{[5\%\ level]}$ =0.569 (max-min. rep); LSD$_{[5\%\ level]}$ =0.36 (max.rep)]; and (*b*) after the 3rd and 2nd cuts of the grass in 2009 and 2010 respectively [LSD$_{[5\%\ level]}$ =1.124 (max-min. rep); LSD$_{[5\%\ level]}$ =0.711 (max.rep). Mean values across the whole experiment [n=12 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=8]. The two curves on both sides of the fitted line represent its 95% confidence interval.

It is also important to highlight that the fertiliser type showed a significant effect with respect to the time (p=0.002). The effect was more evident in post-harvest of wheat in 2008 where SMN was marginally larger in biosolids-treated plots compared with the rest of the treatments. Both OMF_{10}- and OMF_{15}-treated plots resulted in intermediate levels of SMN between biosolids- and urea-treated plots. This is also an indication that mineralisation of organic-N from biosolids and OMF continued beyond the harvest of the crop as highlighted earlier in **Chapter 5**.

For Chippies Field, the data had to be Ln-transformed as residuals did not show a normal distribution. The Ln-transformation of the data resulted in lesser number of units having large residuals. The outputs of both statistical analyses; i.e. prior and after Ln-transformation of the data, are shown in **Appendix A.7.5.** Overall, no significant differences were found between the control and treatments (p=0.214) but there were significant differences in SMN with respect to the fertiliser type (p=0.038) and the nitrogen application rate (p<0.001). The interaction between the fertiliser type and the nitrogen application rate was found to be nonsignificant (p=0.431). Significant differences in SMN were also found with respect to the time (p<0.001) which means that SMN varied significantly in each sampling event. In general, SMN was found to be significantly higher (p<0.001) in post-harvest of wheat in both harvest seasons (2008-09 & 2009-10) compared to the values recorded before the application of the fertiliser in the spring. In this respect, there appeared to be a significantly higher amount of residual SMN accumulated in post-harvest of the 2^{nd} wheat compared with the value encountered after the 1^{st} wheat. This could be attributable to drier soil conditions in the spring of 2010; as rainfall was considerably lower than that of 2009, which affected crop nitrogen uptake and yield leading to increased amount of residual SMN.

It may be argued that this effect occurred also as a result of nitrogen carried over from the previous year (2008-09), especially organic OMF- and biosolids-N, that has been mineralised in the second year after the application. However, this may be discarded since the level of SMN measured before the fertiliser application in 2010 was not significantly different from the base level determined in early spring in 2009. It appeared, therefore, that an important amount of residual nitrogen detected in post-harvest of wheat was lost over the winter time; hence, reducing the level of SMN encountered in early spring. In general, SMN was found to increase with the nitrogen application rate and the concentration of mineral nitrogen in the fertiliser material. This effect was more evident in the second year of the trials, especially in post-harvest.

This was also an indication that drier soil conditions during the period of maximum crop growth and development in the spring affected nitrogen uptake. In contrast to the observations made for Avenue Field, in Chippies Field, urea- and OMF-treated plots produced, respectively, slightly but consistently larger amounts of SMN in post-harvest of wheat both years (2008-09 & 2009-10) compared with biosolids-treated plots.

In Avenue Field, the occurrence of larger amount of rainfall during the critical period for crop yield determination, favoured nitrogen uptake from readily available sources and resulted overall in larger crop yield both years. Simultaneously, as a result of enhanced uptake, SMN was depleted to a further extent in urea- and OMF-treated plots compared with those amended with biosolids. These necessitated more time after the harvest to mineralise its organic-N and to restore the SMN levels for which both urea- and OMF-treated plots exhibited, overall, larger SMN values in the analysis compared with the rest of the treatments. In Chippies Field, it appeared that mineral nitrogen in the fertiliser remained unused by the crop as a result of water stress occurred during the critical period of uptake, also compromising crop yield. Mineralisation of organic-N from biosolids (and also from the organic-N fraction of OMF) did not progress to the same extent to that observed for Avenue Field, possibly, as a result of enhanced water restriction (coarser soil texture) affecting microbial activity.

It is also important to highlight that the surface application of OMF and biosolids imposes itself a restriction to mineralisation of their organic-N fractions which may not be in complete contact with the soil; the effect being accentuated under drier soil conditions. Reduced rainfall in 2010 lessened the opportunities for nitrogen loss by leaching and reduced nitrogen uptake by the crop which accumulated in the soil which was subsequently shown in the analyses conducted in post-harvest of wheat. The changes in SMN recorded for Chippies Field are shown in **Figures 7.18** and **7.19**.

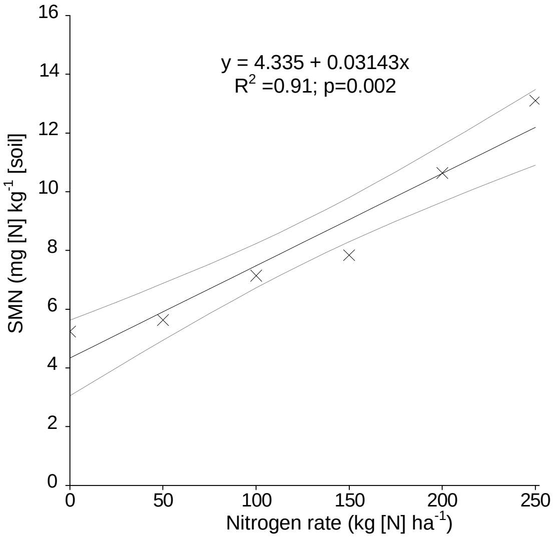


Figure 7.18: Relationship between nitrogen application rate and SMN for Chippies Field in post-harvest of the 2nd wheat crop in 2010 [$LSD_{[5\%\ level]}$ =4.69 (max-min. rep); $LSD_{[5\%\ level]}$ =2.97 (max.rep)]. Mean values across the whole experiment [n=12 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=8]. The 95% confidence interval of the fitted line is also shown.

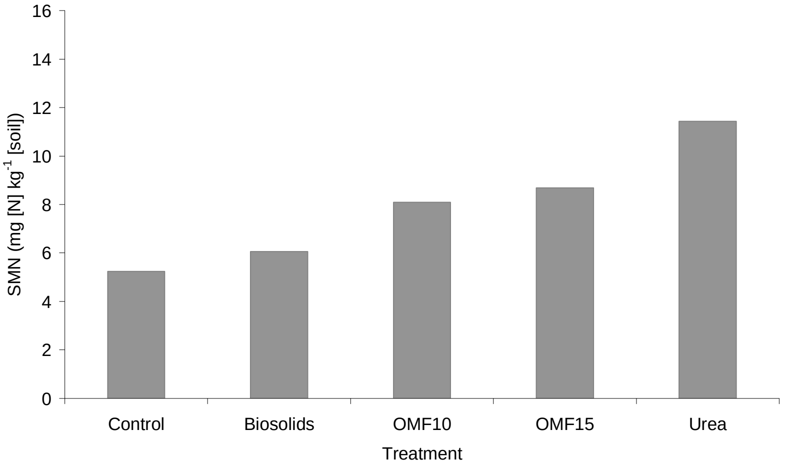
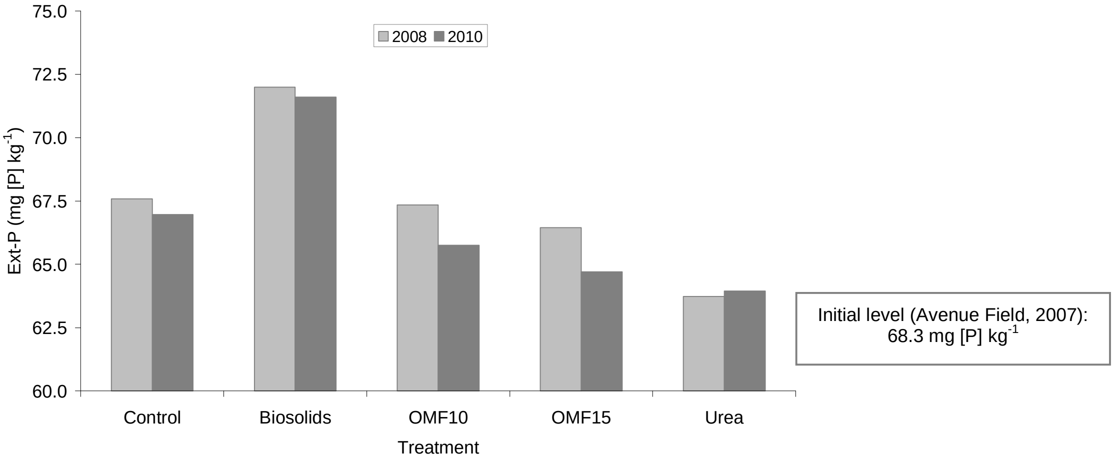


Figure 7.19: Mean SMN recorded for the control plots and the treatments in post-harvest of the 2nd wheat crop in Chippies Field in 2010 [$LSD_{[5\%\ level]}$ =4.62 (max-min. rep); $LSD_{[5\%\ level]}$ =2.75 (max.rep); p=0.004; n=14 except control n=4].

iii. Soil extractable phosphorus

The analysis of soil phosphorus conducted in Avenue Field, indicated that overall, there were not significant differences between the control and the treatments (p=0.923). However, significant differences were found with respect to the fertiliser type (p=0.006). The use of biosolids significantly increased soil extractable-P levels compared with the unfertilised controls. The changes in soil extractable-P recorded for Avenue Field are shown in **Figure 7.20**.



Initial level (Avenue Field, 2007): 68.3 mg [P] kg^{-1}

Figure 7.20: Mean soil extractable-P (Olsen's-P) recorded for the control plots and the treatments in post-harvest of the 2nd wheat crop in 2008 and after the 2nd cut of the grass in 2010 in Avenue Field [$\text{LSD}_{[5\%\ \text{level}]}$ =8.62 (max-min. rep); $\text{LSD}_{[5\%\ \text{level}]}$ =5.53 (max.rep); $\text{LSD}_{[5\%\ \text{level}]}$ =11.07 (min. rep); p=0.850; n=14 except control n=4].

Similar results were obtained by Gavalda et al. (2005) who found that soil Olsen-P was significantly increased in heat-dried sludge-treated plots sown with maize in comparison with urea- and di-ammonium phosphate-treated plots. Their results indicated that soil-P status was significantly increased even after a single fertiliser application. In Avenue Field, the use of urea resulted in an overall decrease in soil extractable-P levels whereas the use of organomineral fertilisers did not change extractable-P levels significantly compared with the unfertilised control plots. There appears to be a relationship between the resultant increase in soil extractable-P and the N:P ratio in the fertiliser material when the fertiliser is applied on the basis of its total nitrogen content. After four years of continuous fertiliser application, soil extractable-P was found to increase as the N:P ratio in the fertiliser applied decreased. Soil extractable-P levels were not significantly affected by the nitrogen, and consequently phosphorus, application rate in biosolids- and OMF-treated plots (p=0.935) or the interaction between the nitrogen application rate and the fertiliser type (p=0.301). However, significant changes with respect to the fertiliser type were found when factoring in the time (p=0.030). Except for the plots treated with biosolids where soil extractable-P increased overtime with respect to the initial level in the soil, a small but consistent decline was observed for the rest of the treatments, including the control plots. This was more evident in urea-treated plots; possibly, as a result of large crop yields; hence, phosphorus off-take in the grain, in addition to the absence of any phosphorus application contained in the fertiliser.

A small reduction in soil extractable-P was encountered in the control plots at the end of the four years trial compared with the initial level (from 68.3 to 66.96 mg [P] kg^{-1}; $LSD_{[5\%level]}$ =8.911). This decline was found to occur to a lesser extent than the rest of the treatments with the exception of biosolids-treated plots which increased from 68.3 to 71.6 mg [P] kg^{-1} ($LSD_{[5\%level]}$ =4.125). The smaller decline recorded for the control plots could be attributable to reduced phosphorus up-take by the crop compared with the rest of the treatments. Since the soil was already well supplied in phosphorus (soil-P index 5) crop yield and P-uptake were therefore restricted by nitrogen supply. Reduced crop yield and lack of phosphorus up-take; effectively, contributed to maintain soil-P level or at least not to deplete it to the same extent as the treatments. The decline in treated plots, although small, may be explained by the fact that only a very small proportion of the phosphorus applied was/became available for which fertiliser-P could not be taken-up in large quantities by the growing crop. In addition, the application of nitrogen enhanced P-uptake by the crop (mainly existing soil-P) which contributed to run-down soil-P levels. In biosolids treated plots, some increase in soil-P level was seen as a result of the application of P with the fertiliser which carries a smaller N:P ratio; hence phosphorus is more concentrated. In addition, as crop growth and yield were restricted by the availability of nitrogen (mostly organic-N) in the biosolids, P-uptake/off-take was also affected providing the scope for some increase in soil-P levels.

Analyses of soil-P conducted in Chippies Field (**Figure 7.21**) showed a similar pattern to that of Avenue Field since no significant differences were encountered between unfertilised control plots and the treatments ($p=0.629$). Unlike Avenue Field, there were not significant effects as a result of the fertiliser type ($p=0.074$) or the nitrogen application rate used ($p=0.061$). However, the use of biosolids resulted overall in relatively higher levels of soil extractable-P than the control and the rest of the treatments (mean value equivalent to 61.87 mg [P] kg^{-1}). Similarly, urea showed the lowest soil extractable-P value (59.28 mg [P] kg^{-1}) which was also the case in Avenue Field. In addition, a significant change in soil extractable-P was not observed for the control plots ($p=0.696$) after two consecutive years of trials which was also attributable to reduced P-uptake.

In the control plots, crop growth and yield were severely affected by nitrogen deficiency which led to reduced phosphorus uptake and subsequent off-take in grain so that the level in the soil did not change significantly (mean values at the start and at the end of the experiment of 61.42 and 61.88 mg [P] kg^{-1} respectively; $LSD_{[5\% level]}$ =6.827).

To certain extent, the changes in soil extractable-P observed in Avenue Field, especially in biosolids-treated plots, may be explained by the over-application of biosolids in the spring in 2007 and also the low N:P ratio of biosolids applied in the spring in 2009 (*c*.0.60) which led to high application rates of P_2O_5 as shown in the fertiliser applications' records for the field (**Appendix A.7.3**). The differences in soil extractable-P with the treatments were also augmented, especially when comparing with urea-treated plots, as a result of the first nitrogen dressing with UAN which resulted, overall, in larger crop yields in urea-treated plots and consequently, increased phosphorus off-take thereby lowering soil-P levels to a larger extent compared with the rest of the treatments. As highlighted earlier, a complete absence of phosphorus application enhanced this process on urea-treated plots. The effect of the over-application of biosolids in the 1st wheat in Avenue Field on soil extractable-P levels was noticeable in post-harvest of the 2nd wheat as shown by the statistical analysis undertaken to compare the initial level with those found in 2008 (p values of 0.033 and 0.044 respectively). This is a distinctive feature from Chippies Field where no significant effects of the fertiliser type upon soil extractable-P levels were observed following two consecutive wheat crops. It is important to highlight that in fixing the amount of nitrogen applied to the experimental plots, the amount of phosphorus applied varied over time since the concentration of phosphorus in biosolids and OMF also changed year on year. However, the amount applied across the different fertilisers within a particular year was constant for each rate. Therefore, any differences between treatments cannot be due to the differences in phosphorus applied over time.

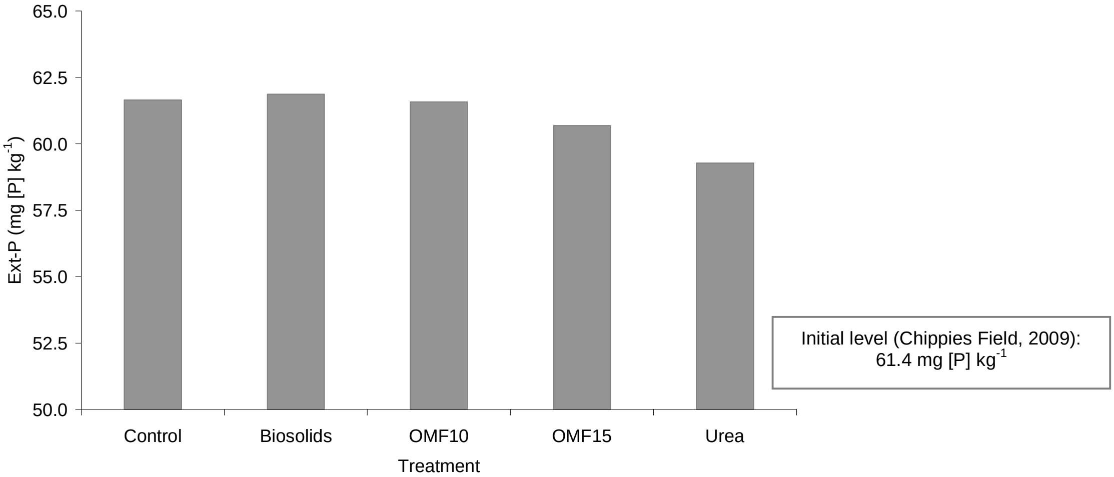


Figure 7.21: Mean soil extractable-P (Olsen's-P) recorded for the control plots and the treatments in post-harvest of the 2nd wheat crop in 2010 in Chippies Field [$LSD_{[5\% level]}$ =5.32 (max-min. rep); $LSD_{[5\% level]}$ =3.16 (max.rep); $LSD_{[5\% level]}$ =6.83 (min. rep); p=0.148; n=14 except control n=4].

iv. Soil extractable potassium

Soil extractable-K was determined prior to the start of the experiments in Avenue Field and subsequently, in post-harvest of the 2nd wheat crop in 2008 and following the 2nd cut of the grass in 2010 which coincided with the end of the field work.

The purpose of these analyses was to quantify the changes in soil extractable-K and soil-K indexes occurred overtime as a result of the continuous application of the four fertilisers tested in the field studies. This was therefore in line with the objectives pursued with the proposed OMF formulations whereby the supplement of potassium via OMF fertilisation would help to maintain existing soil-K indexes (**Chapter 1**). Determinations were made on soil samples corresponding to the unfertilised control plots and also on the plots receiving annually 150 and 250 kg [N] ha^{-1}. This decision was based on the crops' responses to applied nitrogen fertiliser reported earlier (**Sections 7.3.1-2**) which suggested that the recommended nitrogen application rates would be within that range in most circumstances.

In order to reduce the number of analyses, it was decided that if significant changes in soil extractable-K were identified in those plots, a recommendation would be made to further investigate soil-K status at intermediate fertilisation levels. It is important to note that Avenue Field had already a satisfactory soil-K index (3) and that it was the aim to maintain it. The results of the analyses conducted are summarised in **Table 7.9**. Notice that they are reported in mg [K] kg^{-1}; therefore, a conversion of the values to mg [K] l^{-1} was needed to determine the corresponding soil-K index. As for soil extractable-P, this was done by multiplying the value (mass basis) by the soil bulk density in the natural state (1.34 t m^{-3}). Reference will be made in text to the units used.

The statistical analysis indicated that there were not significant differences between the control and the treated plots (p=0.406). There was however a significant effect of the fertiliser type (p=0.024) which was mainly due to the overall decrease recorded in urea-treated plots (mean values across the whole experiment of 207.9 and 189.7 mg [K] kg^{-1} for the controls and urea-treated plots respectively; LSD$_{[5\% \text{ level}]}$ =17.06). Overall, significant effects of the fertiliser application rate or the interaction between the fertiliser type and the rates were not observed (p-values of 0.769 and 0.306 respectively).

Table 7.9: Determination of extractable-K in Avenue field between 2007 and 2010 [LSD$_{[5\%\ level]}$ =43.0 (min.rep); 39.25 (max-min rep); 35.11 (max.rep); p=0.183].

Unit		--------------------------- **[mg K kg^{-1}]**	----------------------------		
Initial level, 2007 (n=3)		**211.7 (K-index 3)**			
Treatment/Year	**n=**	**2008**	**K-index**	**2010**	**K-index**
Control	4	207.6	3	200.8	3
Biosolids (150 kg [N] ha^{-1})	3	204.1	3	188.6	3
Biosolids (250 kg [N] ha^{-1})	2	201.4	3	166.5	2+
OMF$_{10}$ (150 kg [N] ha^{-1})	3	223.7	3	175.8	2+
OMF$_{10}$ (250 kg [N] ha^{-1})	2	290.3	3	150.1	2+
OMF$_{15}$ (150 kg [N] ha^{-1})	3	240.9	3	170.9	2+
OMF$_{15}$ (250 kg [N] ha^{-1})	2	275.4	3	163.3	2+
Urea (150 kg [N] ha^{-1})	3	212.3	3	155.1	2+
Urea (250 kg [N] ha^{-1})	2	192.3	3	149.6	2+
Mean	**24**	**226.2**	**3**	**171.0**	**2+**
SD	-	**37.30**	**-**	**24.65**	**-**

Interestingly, there were significant changes in soil extractable-K overtime ($p<0.001$) which was also observed with respect to the fertiliser type (p=0.02). The changes overtime were significantly different in all three years but a greater difference was recorded between 2008 and 2010 which led to a reduction in soil-K indexes from 3 to 2+ in most of the treatments (mean values were 211.7, 226.2, and 171.0 mg [K] kg^{-1} for 2007, 2008 and 2010 respectively; LSD$_{[5\%\ level]}$ =13.32). Therefore, the incorporation of straw following the harvest of wheat in 2007 and 2008, contributed to maintain soil-K levels. In addition, the changes indicated above suggest a significant effect of the crop upon soil extractable-K levels following the introduction of rye grass in 2009.

The decrease observed in soil-K status occurred in all treatments to a similar extent and that is the reason why the p-value in **Table 7.9** does not indicate a significant effect. However, it can be seen from the table that soil extractable-K was reduced further in the plots receiving 250 kg [N] ha^{-1}. Therefore, it can be stated that the overall decline was related to the level of biomass production (**Tables 7.7a-b**) and also to the supply of K via fertiliser in the OMF. In OMF-treated plots, it prevented, to certain extent, the decline in soil-K levels while it maintained dry matter yield levels. In biosolids-treated plots, despite there was not addition of K, the decline was smaller because dry matter yield in the grass' years was significantly lower than the rest of the treatments and the same is true for the control plots.

In urea-treated plots, there was a decrease in soil extractable-K of *c*.50 mg [K] kg^{-1} on average compared to the levels in post-harvest of wheat in 2008 which is the combination of high biomass production and no addition of K in the fertiliser. Dry matter yield, however, was not affected by the level of K in soil simply because the soil supply was still satisfactory at the end of the experiment (2+) but it may be monitored in the long term. An important aspect of the management of the grass in Avenue Field is that there was not complete removal of plant material from the field such as in hay or intake by livestock. This suggests that, assuming losses from the soil by leaching or other way were minimal, large amounts of potassium were actually in-plant for which the changes recorded in the soil-K index (from 3 to 2+ in most treatments) were only temporary and may be restored/stabilised in the long term.

Johnston and Goulding (1992) reported mean annual losses of potassium in drainage water of *c*.0.5 mg [K] l^{-1} from a sandy clay loam occupied by herbage crops. The same work, based on data for USA and Europe, indicated losses of potassium by leaching of *c*.1 kg [K] ha^{-1} for every 100 mm of rain. In a situation of intensive grass production, potassium fertilisation (in addition to that provided with OMF) may be required to sustain both soil-K indexes and high levels of dry matter yield. In this respect, the work of Johnston et al. (2001a-b) and later Milford and Johnston (2007) highlighted the importance of maintaining an adequate soil-K status which has a significant influence upon crop uptake and crop response to nitrogen. Yield response to the application of nitrogen is negatively affected by low levels of soil extractable-K; e.g. below the target level as specified in RB209 (MAFF, 2000). The later work concludes that the agronomic response of a crop is highly dependent on the underlying physiological interacting effects of nitrogen and potassium which are associated with tissue hydration and osmotic adjustments. The same work by Milford and Johnston (2007) argued that available nitrogen will be used with low efficiency in soils containing low soil extractable-K to allow the crop to fully adjust osmotically to changes in tissue hydration.

v. Soil pH

Soil analyses conducted in Avenue and Chippies Fields showed that, overall, there were not significant changes in soil pH between the control and the treated-plots (p-values of 0.379 and 0.317 for Avenue and Chippies Fields respectively). In none of the two experimental sites, significant changes in soil pH were observed as a result of the fertiliser type (p-values of 0.572 and 0.138 respectively), the nitrogen application rate (p-values of 0.475 and 0.608 respectively) or the interaction between the fertiliser type and the nitrogen application rate used (p-values of 0.244 and 0.426 respectively).

However, there appeared to be a small decline in soil pH observed in post-harvest of wheat in 2008 in Avenue Field with respect to the initial value recorded in March 2007 from 7.12 to 7.08 ($LDS_{[5\% \text{ level}]}$ =0.052); however, the overall effect was nonsignificant between-years (p=0.058). This appeared to be only a temporary effect as soil pH levels were restored during the grass years. It could have also been influenced by the timing of sampling immediately after harvest. In Chippies Field, the differences in soil pH recorded overtime were nonsignificant (p=0.146).

vi. Soil organic matter

The levels of SOM recorded for Avenue and Chippies Fields are shown in **Figures 7.22-7.24**. Soil analyses conducted in Avenue and Chippies Fields showed that, overall, there were not significant changes in SOM between the control and the treatments (p-values of 0.781 and 0.219 encountered for Avenue and Chippies Fields respectively). For both sites, the changes observed in SOM were not significant with respect to the fertiliser type (p-values of 0.053 and 0.852), the nitrogen application rate (p-values of 0.076 and 0.275) or the interaction between the fertiliser type and the nitrogen application rate (p-values of 0.37 and 0.467). In Avenue Field, however, there was a significant difference in SOM between the initial level (2007) and the mean value across the whole experiment recorded after the 2nd cut of the grass in 2010 (mean values of 3.88% and 4.25% respectively; $LSD_{[5\%\text{level}]}$ =0.057). On the contrary, in Chippies Field, SOM levels did not change significantly (p=0.221) compared with the initial value recorded in 2009 following two consecutives winter wheat crops (mean values of 3.43% and 3.47% respectively).

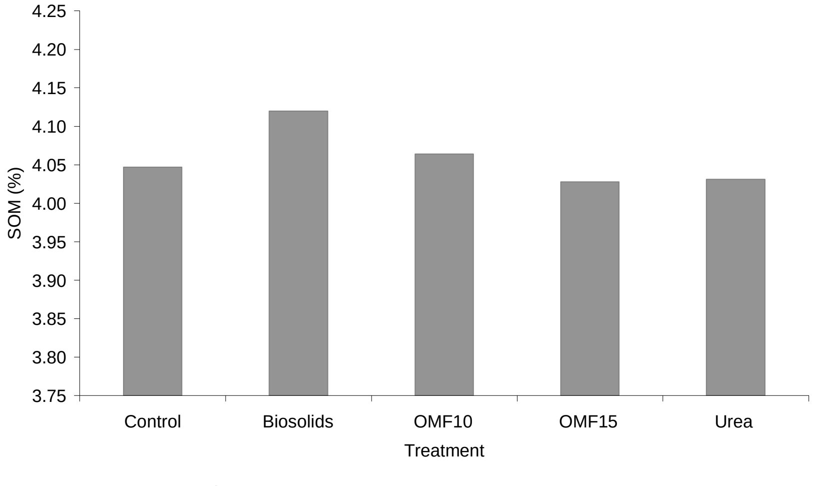


Figure 7.22: SOM recorded for the control plots and the treatments in Avenue Field in 2010 [$LSD_{[5\% \text{ level}]}$ =0.1307 (max-min. rep); $LSD_{[5\% \text{ level}]}$ =0.0776 (max.rep); p=0.061; n=14 except control n=4].

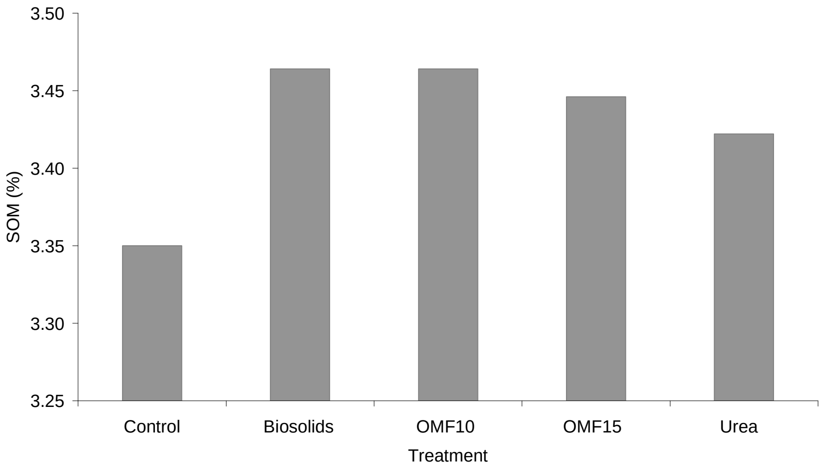


Figure 7.23: SOM recorded for the control plots and the treatments in Chippies Field in 2010 [LSD$_{[5\%\ level]}$ =0.1710 (max-min. rep); LSD$_{[5\%\ level]}$ =0.1016 (max.rep); p=0.815; n=14 except control n=4].

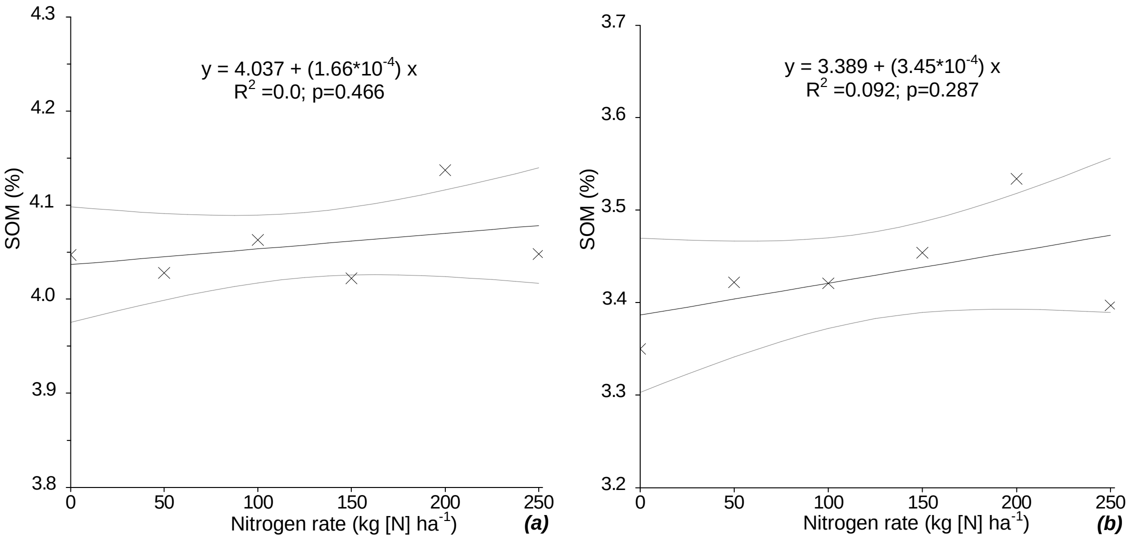


Figure 7.24: Relationship between nitrogen application rate and SOM; (*a*) Avenue Field, and (*b*) Chippies Field in 2010 [LSD$_{[5\%\ level]}$ =0.174 (max-min. rep); LSD$_{[5\%\ level]}$ =0.101 (max.rep)]. Mean values across the whole experiment [n=12 except controls n=4, and plots treated with 250 (kg [N] ha^{-1}) n=8]. The two curves on both sides of the fitted line represent its 95% confidence interval.

Although determination of SOM after the 2nd wheat crop in Avenue Field was not conducted, it is expected that the changes in SOM levels would have followed a similar trend to that indicated for Chippies Field. On that basis, it is possible to state that the changes in SOM levels encountered in Avenue Field were mainly due to the effect of the crop and to a much lesser extent as a result of the fertiliser type or the nitrogen application rate used.

The introduction of the grass in the rotation is understood to have significantly increased SOM levels compared with those found in the field under continuous arable cropping. In fact, when comparing the initial SOM levels in 2007 and the mean value across the whole experiment in 2010, a significant difference was found (mean values of SOM of 3.87% and 4.25% respectively; $LSD_{[5\% \text{ level}]} = 0.02$; $p<0.001$). An important aspect of the management of the grass in Avenue Field is that there was not removal of plant material from the plot after the harvest; except for the four square sample taken after the cut. The grass removed following the cut of the four-square sample constituted only a small proportion of the total biomass produced in the plot. The experimental site was mowed after the samples were taken but the grass cut was left on the soil surface which could have favoured the increase in SOM levels during the two years under grass. Although this is not the common practice; i.e. grass would be completely removed by means of grazing or harvesting, there were some practical advantages regarding the management of the site including the lack of equipment for collecting the grass from the field and also the availability of labour to conduct the operations. In addition, for both fields, there appeared to be an indication that the use of biosolids would contribute to increase SOM levels. As highlighted above, the differences in SOM levels as a result of the fertiliser type were not significant; however, biosolids-treated plots consistently showed relatively higher SOM levels compared with the rest of the treatments. Johnston (1975) indicated that the continuous use of biosolids and organic amendments contributes to maintain/increase SOM levels. For all other treatments, SOM remained at approximately the same levels as the control plots which could be attributable to the larger biomass production observed overall and the fact that both the straw and the grass cut were returned back to the soil after the harvest.

vii. Heavy metals in soil

Analyses of heavy metals were conducted on soil samples taken in 2007 prior to the start of the experiments at the College Farm in Avenue Field and subsequently in post harvest of the 2nd wheat in 2008 and following the 2nd cut of the grass in 2010 which coincided with the end of the field studies. The potential risks associated with the build up of heavy metals in the soil and were reviewed in **Chapter 2**. The purpose of this set of analyses was to determine whether there was a build up of selected heavy metals after continuous application of the four fertilisers tested. As highlighted for soil extractable-K, determinations were made on soil samples corresponding to the unfertilised control plots and also on the plots receiving 150 and 250 kg [N] ha^{-1} per year since the recommended nitrogen application rates were expected to be within that range.

It was decided that if significant increases in the concentration of heavy metals were detected overtime in those plots, a recommendation would be made later to investigate their accumulation at intermediate rates. The metals determined were Cd, Cu, Zn and Pb, and the results are summarised in **Table 7.10**. Soil pH was reported earlier in **Section 7.3.3-v**; but the values corresponding to the treatments analysed are quoted in the table to aid in the interpretation of the results obtained. It is important to highlight that it was not the main purpose of this work to conduct an in-depth investigation on heavy metals and their complex soil-crop interactions but to provide an indication of potential cumulative effects in the soil as a result of the use of OMF in crop production. The heavy metals determined are of importance due to the well documented effects on the crops, livestock and their potential transfer on to the food chain.

Table 7.10: Determination of heavy metals in Avenue field between 2007 and 2010.

Unit		**---------------------------- [mg kg^{-1}]----------------------------**								**-**	
Determination		**Cd**		**Cu**		**Zn**		**Pb**		**Soil pH**	
Initial level, 2007 (n=3)		0.17		0.01		0.05		0.02		7.11	
Treatment/Year		**2008**				**2010**				**-**	
Determination	**n=**	**Cd**	**Cu**	**Zn**	**Pb**	**Cd**	**Cu**	**Zn**	**Pb**	**2008**	**2010**
Control	4	0.17	0.01	0.05	0.01	0.17	0.01	0.05	0.02	7.24	7.12
Biosolids (150 kg [N] ha^{-1})	3	0.26	0.01	0.05	0.01	0.18	0.01	0.05	0.02	7.21	7.19
Biosolids (250 kg [N] ha^{-1})	2	0.18	0.02	0.06	0.02	0.15	0.01	0.05	0.02	7.08	6.95
OMF$_{10}$ (150 kg [N] ha^{-1})	3	0.19	0.01	0.05	0.02	0.18	0.01	0.04	0.02	7.07	7.23
OMF$_{10}$ (250 kg [N] ha^{-1})	2	0.19	0.01	0.05	0.02	0.15	0.01	0.05	0.02	6.80	6.95
OMF$_{15}$ (150 kg [N] ha^{-1})	3	0.15	0.01	0.04	0.02	0.15	0.02	0.06	0.02	7.02	7.16
OMF$_{15}$ (250 kg [N] ha^{-1})	2	0.21	0.01	0.06	0.03	0.19	0.01	0.07	0.02	7.05	7.15
Urea (150 kg [N] ha^{-1})	3	0.23	0.01	0.05	0.02	0.17	0.01	0.05	0.02	7.12	7.13
Urea (250 kg [N] ha^{-1})	2	0.17	0.01	0.05	0.02	0.15	0.01	0.04	0.02	7.07	7.22
Mean	**24**	**0.19**	**0.01**	**0.05**	**0.02**	**0.17**	**0.01**	**0.05**	**0.02**	**7.07**	**7.12**
SD	-	**0.03**	**0.00**	**0.01**	**0.01**	**0.02**	**0.00**	**0.01**	**0.00**	**0.13**	**0.11**

Cd: LSD$_{[5\% \text{ level}]}$ =0.1104 (min.rep); 0.101 (max-min.rep); 0.09 (max.rep); p=0.625.
Cu: LSD$_{[5\% \text{ level}]}$ =0.0033 (min.rep); 0.003 (max-min.rep); 0.0027 (max.rep); p=0.431.
Zn: LSD$_{[5\% \text{ level}]}$ =0.0159 (min.rep); 0.0145 (max-min.rep); 0.0129 (max.rep); p=0.431.
Pb: LSD$_{[5\% \text{ level}]}$ =0.0076 (min.rep); 0.0069 (max-min.rep); 0.0062 (max.rep); p=0.170.

The changes recorded overtime for **Cd** were nonsignificant (p=0.169) and they were not affected by the fertiliser type (p=0.824), the fertiliser application rate (p=0.398) or the interaction between the two factors (p=0.357). Similarly, for **Cu** significant changes in its concentration in the soil were not observed overtime (p=0.062) and it was not significantly affected by the fertiliser type (p=0.121), the application rate (p=0.401) or the interaction between the two factors (p=0.933).

In addition, the changes in observed in the concentration of **Zn** overtime were not significant (p=0.062) and significant changes as a result of the fertiliser type (p=0.121), the application rate (p=0.401) or the interaction between the two (p=0.933) could not be detected. Overall, there were not significant differences in the concentration of **Pb** between the control and the treatments (p=0.07) and the same was observed with respect to the fertiliser type (p=0.616) and the interaction between the fertiliser type and the application rate (p=0.788). However, there was, overall, a significant effect of the application rate (p=0.006) which was observed when the fertilisers were applied at 250 kg [N] ha^{-1} (mean values of 0.017 and 0.02 mg [Pb] kg^{-1} for the control and the plots fertilised with 250 kg [N] ha^{-1}; LSD$_{[5\% \text{ level}]}$ =0.003). Although the effect was statistically significant compared with the control, the change encountered in the concentration of Pb at this fertilisation level was very small, it may be advisable to monitor Pb levels in the long term if the same fertilisation regime was to be continued. Overall, the concentrations of selected heavy metals in the soil were found to be well below the maximum permissible/advisable concentrations indicated in the Revised Soil Code (MAFF, 1998b), quoted earlier in **Chapter 2**, and given the soil pH values encountered at the experimental site. Therefore, it can be stated that the application of biosolids, OMF$_{10}$, OMF$_{15}$ and urea at rates ≤250 kg [N] ha^{-1} should not present a risk if the fertilisers were to be applied under similar soil-crop conditions of Avenue Field.

7.4 Overall discussion

The results reported for TN$_{grain}$ showed that it tended to increase with the nitrogen application rate for the range used in Avenue Field which appears to be in agreement with the results obtained by Benzian and Lane (1979 & 1981) and Johnston and Poulton (2009) who found linear responses between TN$_{grain}$ and nitrogen rate (range 48-288 kg [N] ha^{-1}). These results however do not closely agree with those previously reported by Boquet and Johnson (1987) who found that the application of nitrogen (range 0-100 kg [N] ha^{-1}) did not affect grain protein content but did increase total protein content per hectare as a result of the increase in grain yield. By contrast, their work indicated that P and K fertilisation were not found to have a significant effect on grain protein or mineral composition in the grain. Fertilisation with urea showed R$_N$ to be in the range of 33%% to 68% compared with biosolids and both OMF products which showed R$_N$ ranging between 8% and 44%, and between 32% and 61% respectively. Similarly, the application of urea to the experimental plots consistently showed higher levels of TN$_{grain}$ compared with OMF$_{10}$ and OMF$_{15}$ which have, in addition to nitrogen, variable amounts of P and K in their formulation.

Therefore, the increase in the content of TN_{grain} may be associated not only with the nitrogen application rate but also with the concentration of mineral nitrogen in the fertiliser applied. It also appeared from the results obtained in Avenue and Chippies Fields that the application of phosphorus and potassium combined with nitrogen in the form of an NPK fertiliser was of little value for yield enhancement since, overall, crop yield in OMF-treated plots was found to be lower compared with urea-treated plots given an already satisfactory level of soil-P and -K. The range of values of TN_{grain} obtained in Avenue Field were on average below the target for feed wheat varieties which is 2% [TN_{grain}] (w w^{-1}) as recommended by MAFF (2000). They were also lower than those reported by Rothamsted Research (2006) and Johnston and Poulton (2009) for the Broadbalk Experiment (winter wheat *cv*. Hereward; harvest seasons 1996-2000) for a similar range of nitrogen application rates (≤240 kg [N] ha^{-1}). It possible, however, the occurrence of a dilution effect as a result of the relatively large grain yields obtained on average in Avenue Field in both harvest seasons (6.9 and 10.3 t [grain] ha^{-1} for 2006-07 & 2007-08 respectively). Stepwise regression analyses conducted by Boquet and Johnson (1987) revealed a significant linear relationship between specific kernel weight and the increase in the nitrogen application rate and a lesser positive association of kernel number per spike with nitrogen rate. The authors also noted that changes in specific kernel weight showed a lack of consistency between years with respect to its relationship with the nitrogen application rate; possibly, as a result of late-season foliar diseases which affected kernel development.

The results obtained for Avenue and Chippies Fields showed, in general, an increase in the W_{1000} grains and the number of ears per m^2 with increasing nitrogen application rates (range 0-250 kg [N] ha^{-1}). In most cases, the maximum values for both parameters were reached at a rate of 200 kg [N] ha^{-1} which may suggest, in agreement with Boquet and Johnson (1987), the possibility of late-season foliar diseases, especially in wetter years; e.g. 2007-08. However, it cannot be stated conclusively with the data available that the effect of the nitrogen rate above 200 kg [N] ha^{-1}, and the consequent decline at 250 kg [N] ha^{-1}, on the W_{1000} grains was directly related to the increase in diseases late in the season. There also appears to be a lack of consistency in the relationship between the maximum W_{1000} grains and the corresponding nitrogen application rates (range 150-350 kg [N] ha^{-1}) across years. Although data was not recorded on the effect of the fertiliser type on tillering, it appeared that an important proportion of the increase in grain yield in urea- and OMF-treated plots with respect to biosolids-treated plots resulted from increased number of fertile tillers per square meter and perhaps the number of grains per ear, and to a lesser extent to the W_{1000} grains.

In this respect, Slafer (2003) highlighted that the two major crop yield components in wheat are the number of grains per square meter and the weight of the grains. Crop yield can be incremented by increasing the number of grains which is fixed by the canopy, and/or the weight of the grains which is determined by the crop and the crop-environment interactions in post-anthesis (Slafer, 2007). These interactions determine the rate and duration of the grain filling phase (Slafer, 2007). Stone and Savin (1999) suggested that during the period immediately post-anthesis, the potential size of the grain is defined since the number of cells in the endosperm is determined.

Experimental work conducted by Slafer and Andrade (1989 & 1993) showed that, in the absence of water stress, varietal and temporal differences in grain yield were mainly due to the number of grains per square meter. In their work, individual grain weight showed the opposite pattern; the lowest grain weight being the highest yielding variety, which reinforces the fact that increments in grain yield between cultivars can be better explained by increments in the number of grains per square meter. Slafer and Andrade (1993) also indicated that the number of grains per spike was the main trait associated with the number of grains per square meter and therefore grain yield. Foulkes et al. (2007) had also indicated that the physiological basis of genetic gain in yield potential have shown grains per square meter, generally as a result of increased grains per ear, and harvest index to be positively correlated with grain yield.

It is generally acknowledged that the critical period for grain yield in wheat is during pre-anthesis (Fischer, 1985; Thorne and Wood, 1987; Savin and Slafer, 1991; Slafer and Andrade, 1993). Under similar conditions of water and sunlight stresses, crop yield can be simplified to be a function of the nutritional status of the soil which, in turn, also depends on the fertiliser applied and the availability of the nutrients in the fertiliser. Earlier studies (Siddique et al., 1989; Slafer and Andrade, 1993) suggested that the number of florets is related to the number of fertile florets. The occurrence of a nutritional stress; e.g. restricted nitrogen supply, can affect the survival of florets and ultimately the number of grains. Kirby (1988) indicated that the death of florets is due to competition for photo-assimilates between the ears and the stems at the time the ears show the maximum growth rate (the ear-growth phase concludes at anthesis; Kirby, 1988).

The ability of the fertiliser to supply nitrogen to the crop prior to the critical period where crop yield is defined helps to explain differences in grain yield, mainly, as a result of differences in the number of grains, and to a lesser extent, to the weight of the grain.

This supports the fact that, on average, grain yield and all the measured crop yield components tended to increase with the concentration of available nitrogen in the fertiliser applied to the crop. Adequate supply of readily available nitrogen to the crop reduced the chances for nutritional stress prior to the critical period for determination of grain yield. The values of harvest index reported for Avenue and Chippies Fields were above (*c*.10%) those encountered by Foulkes et al. (2007) for UK conditions. However, the work conducted by Spink et al. (2000) showed harvest indexes greater than 0.6 which has been reported to be the upper limit for North-western Europe with the current spectrum of crop varieties available (Foulkes et al., 2007). The results obtained for some of the crop yield components measured; e.g. ears per m^2, total biomass and harvest index, consistently showed that the maximum values were achieved at a nitrogen rate equivalent to 200 kg [N] ha^{-1}. Conversely, the nitrogen application rates required for maximum grain yield (**Table 7.4a**), as estimated from the equations given in **Figures 7.4-7.7**, resulted on average in nitrogen rates above 200 kg [N] ha^{-1}. This suggests that if crop yield could be increased as predicted by the response curves, the increment would have to come from increments in the number of grains per ear. This may be explained by the crop being unequally affected by environmental stresses; e.g. water shortage at/around the critical period for grain yield determination, depending on the level of fertilisation. For instance, increased above-the-ground biomass in the crop fertilised at 250 kg [N] ha^{-1} compared with that receiving a lower nitrogen rate, required a larger amount of water to sustain an increased evapotranspiration rate around the critical growth period. Under conditions of stress, grain yield may be disproportionally affected compared with the plots that received a lower nitrogen rate.

Brooking and Kirby (1981) proposed that floret death may be due to competition for limited resources. The potential number of florets and tillers formed up until anthesis is usually reduced by death for which this phase is crucial in establishing the yield components and therefore determining yield (Kirby, 1988). The overall effect is not explicitly reflected on the maximum grain yields calculated from the response curves. White and Wilson (2006) found that excessive leaf growth and tiller production, as a result of nitrogen fertilisation in the spring, could not be sustained by low availability of soil nitrogen later in the growing season resulting in poorer partitioning of biomass to grain, the effect being more evident as nitrogen fertilisation level was increased. A rapid release of mineral nitrogen from OMF would produce a similar effect to that reported by White and Wilson (2006), especially at the higher range of rates used. Mineralisation of organic-N from OMF would not be sufficient to sustain nitrogen demand by the crop later in the season; e.g. at/around anthesis, which compromised grain yield.

This effect was not as evident with urea since the excess mineral nitrogen not taken-up by the crop remained in the soil and was available for uptake later in the season thereby preventing grain yield, and its components, from declining to the same extent as OMF. On this basis, the application of OMF may be split into two (o more) dressings depending on the rate to ensure the nitrogen demand by the crop is covered not only during the vegetative phase but also prior to anthesis.

Following the recommendations given in RB209 (MAFF, 2000) it is reasonable to state that nitrogen recommendations above 120 kg [N] ha^{-1} may be sub-divided into two applications. Comparing the results reported in **Table 7.4** for both OMF products and urea, it is clear that maximum grain yield increased with the use of a more concentrated nitrogen source. It is also evident that a more concentrated N-product necessitated a lower nitrogen rate to reach the maximum grain yield. The use of biosolids required, overall, a similar level of nitrogen fertilisation to urea, but grain yield was *c*.30% lower. This value is close to 40% lower than urea when removing the data corresponding to the yield obtained in 2006-07 when UAN was applied on top of the rate specified by the treatments. Another feature is the large variability shown on the yields obtained with biosolids and the apparent effect of environmental conditions on the conversion of organic-N into readily available forms, especially, during the spring of 2010.

The most economic nitrogen application rates (MERN) for each of the fertiliser materials tested could not be determined with the data available up to this point. The choice of a particular fertiliser up until this point can only be made based on the agronomic performance in relation to the various crop and soil parameters measured. The economic analysis of the crop responses to applied fertiliser will be addressed later (**Chapter 8**) since a fertilisers' price analysis is also required. The economic analysis is; however, supported on the technical data coming from the various experiments conducted. The assessment of the fertilisers' agronomic performance has shown that urea generally outperformed OMF_{15}, OMF_{10} and biosolids. On the contrary, biosolids significantly underperformed compared with the rest of the fertilisers used while both OMF_{10} and OMF_{15} showed similar results overall. Therefore, it is reasonable to state, as a preliminary conclusion and from the agronomic point of view that the use of OMF was advantageous compared with biosolids. In terms of crop yield, there appeared to be a marginal benefit from the use of OMF_{15} compared with OMF_{10} both in winter wheat and rye-grass which was consistent with the crop yield components measured. Of particular interest was the significant relationship ($p=0.025$) found between the nitrogen application rate and total-above-the-ground biomass.

At the lower range of nitrogen application rates, grain yield was reduced by nitrogen supply which restricted the size of the canopy; i.e. total-above-the-ground biomass; hence, affecting the amount of radiation intercepted by the crop and the radiation use efficiency (Abbate et al., 1995). The same effect may be expected when nitrogen supply is restricted by the type of nitrogen fertiliser used regardless of the nitrogen application rate. The differential crop yield between OMF_{15} and OMF_{10} was found to be 224 kg [grain] ha^{-1} in winter wheat and 276 kg [DM] ha^{-1} in rye grass on average across the years. The overall improved performance of OMF_{10} compared with OMF_{15} during the harvest season of 2007-08 can be attributable to poorer physical characteristics of the former compared with the latter as shown earlier (**Chapter 3**).

The fertiliser application both in Avenue and Chippies Fields significantly increased TN_{soil} levels after two consecutive wheat crops. In Avenue Field, the effect also responded to the high nitrogen levels applied in 2007. Previous studies (Vaidyanathan et al., 1987; Sylvester-Bradley, 1993) indicated that significant amounts of soil nitrogen are taken-up by the crop from the soil. For example, for winter wheat grown after a cereal crop, this amount can be as high as 70 kg [N] ha^{-1} and up to 110 kg [N] ha^{-1} when it is preceded by oilseed rape or peas (Vaidyanathan et al., 1987). The rates applied at the experimental sites did not take account of any potential soil nitrogen supply for which a build-up of TN_{soil} is not surprising. This was more evident when the nitrogen application rates were increased; in fact, a positive (significant) correlation between the nitrogen application rate and TN_{soil} was found for both sites as shown earlier in **Section 7.3.3-i.**

In this respect, the studies conducted by Sylvester-Bradley (1993) indicated that a winter feed wheat yielding 8 t [grain] ha^{-1} and fertilised typically with 200 kg [N] ha^{-1} would result in a positive N-balance in the soil of *c.*65 kg [N] ha^{-1} since TN_{uptake} and $TN_{off\text{-}take}$ (grain) were estimated to be 175 and 135 kg [N] ha^{-1} respectively. Based on these figures, Sylvester-Bradley (1993) also suggested that if the amount of N-fertiliser applied is of similar order of magnitude to TN_{uptake} and that nitrogen supply by the soil is not computed in the fertiliser recommendation, then it is clear that fertiliser-N can rarely be recovered in full. The excess nitrogen applied contributed to build-up TN_{soil} which has been shown to occur at both sites, Avenue and Chippies Fields. The work of Sylvester-Bradley (1993) suggested that there is scope for reducing nitrogen fertilisation if soil nitrogen supply could be accurately predicted for the main growing season. However, estimation of soil nitrogen supply on the basis of SMN does not appear to be reliable since significant differences between the control and the treatments could not be detected overall at any of the two experimental sites.

The effect of the fertiliser type on SOM was found to be nonsignificant; however, there appeared to be an effect of the crop on the overall increase in SOM levels recorded after the introduction of rye grass in Avenue Field in 2009. Similarly, the changes recorded overall on soil phosphorus status (soil-P index) were nonsignificant for none of the two OMF products which appeared to be in line with the objectives pursued with both formulations.

As highlighted in **Chapter 3**, the formulation of both OMF products aimed at maintaining soil-P indexes when the application of OMF was made on the basis of nitrogen. This is of particular interest given the already satisfactory soil-P levels at both experimental sites. Soil-P levels in OMF-treated plots remained close to the initial levels (**Table 7.2**) over the range of nitrogen application rates (mean values of soil extractable-P were 67.2 and 66.5 for OMF_{10} and OMF_{15} respectively in Avenue Field – $LSD_{[5\% \text{ level}]}$ =2.93; and 60.7 and 61.6 mg [P] kg^{-1} for OMF_{10} and OMF_{15} respectively in Chippies Field – $LSD_{[5\% \text{ level}]}$ =2.11).

Similarly, a small increase in soil-P (from 67.62 to 70.61 mg [P] kg^{-1} and from 61.65 to 61.87 mg [P] kg^{-1} in Avenue and Chippies Fields respectively for the same LSD values as above) was encountered in biosolids-treated plots; the effect being more evident in Avenue Field which received fertiliser applications over four consecutive years. The changes recorded on soil-P status in both sites, although small, cannot be explained by changes in soil pH. In this respect, there were not significant changes in soil pH as a result of the fertiliser type used or the level of N-fertilisation during the length of the trials. It is important to highlight that at the time the field experiments were completed, soil-P indexes remained unchanged at index 5 at both experimental sites. These findings are supportive of the proposed formulations for OMF; they also emphasise the importance of the fertiliser's formulation on soil phosphorus run-down/build-up and the effect of the fertiliser's N:P ratio on soil phosphorus levels.

7.5 Conclusions

The main conclusions coming from **Chapter 7** are summarised below:

- In terms of crop yield, it was found that in both crops (winter wheat and rye grass), urea generally outperformed biosolids, OMF_{10}, and OMF_{15}. A similar observation can be made for the various crop yield components measured in winter wheat.
- The use of OMF_{10}, OMF_{15} and urea in winter wheat resulted in differential mean yields (relative to biosolids) equivalent to 111.5%, 123%, and 142.4% respectively. For rye grass, these were approximately 122%, 133%, and 134% respectively.

- It was also found that, for both OMF products on average, an input of $0.82*N_{max}$ yielded $0.98*Y_{max}$, and that this relationship was found to be similar to that of urea ($0.83*N_{max}$ yielded $0.99*Y_{max}$). Biosolids, required an input of $0.61*N_{max}$ to yield $0.92*Y_{max}$ but yield was between 22% and 34% lower than OMFs and urea respectively.
- It is reasonable to state that for the range of fertiliser products tested, and regardless of the nitrogen rate used, crop yield was enhanced when the nitrogen concentration in the fertiliser, and in particular, the concentration of readily available nitrogen were increased. It appeared that the ability of the fertiliser to supply nitrogen to the crop at/around the critical period of crop yield determination (pre-anthesis) was an important factor influencing grain yield in winter wheat.
- Biosolids-N did not become available at a rate sufficient to sustain a yield level (and its components) comparable, for instance, to that obtained with OMF. In general, OMF supplied sufficient nitrogen to the crop following the application. OMF-N was initially released from its mineral-N fraction and consequently some of the yield components were of similar order of magnitude to those of urea. However, as the crop approached the critical stages the rate of nitrogen supply decreased affecting grain yield. Grain yield in OMF-treated plots did not decline to the same extent to that recorded in the crop amended with biosolids; possibly, as a result of larger above-the-ground biomass. From the above, it may be appropriate to state that supplementary nitrogen may be required at certain stages of crop growth.
- The quadratic functions used to describe the response of winter wheat to the application of nitrogen provided generally acceptable fits. Such form of equations allowed deriving N_{max} and the corresponding Y_{max}. For the 2nd wheat crop fertilised with biosolids and OMF, the nitrogen to yield relationships can also be explained by linear functions.
- Quadratic functions were shown to have acceptable fits to the data obtained for grass (dry matter yield). Linear relationships were also possible for the response to the application of biosolids. For grass amended with biosolids, the calculated N_{max} were above the range of nitrogen application rates used which also explains the linearity of the response.
- In Avenue Field, TN_{soil} was significantly increased as a result of the fertiliser application and there was a positive correlation between TN_{soil} and the nitrogen application rate.

The overall effect of the fertiliser type on the increase in TN_{soil} was largely due to the application of biosolids which was also significantly higher than the rest of the fertilisers applied. The values of TN_{soil} recorded in OMF_{10}-, OMF_{15}- and urea-treated plots were not statistically different. In Chippies Field, the application of fertiliser also increased TN_{soil} compared to the initial levels and there was a positive correlation between TN_{soil} and the nitrogen rate used. However, no significant differences were encountered for the fertiliser type.

- The analyses of soil extractable-P in Avenue and Chippies Fields indicated that, on average, the use of OMF_{10} and OMF_{15} did not change soil-P levels significantly compared with the unfertilised controls.
    - In Avenue Field, the use of biosolids and urea significantly increased and decreased, respectively, soil extractable-P levels compared with the untreated control soils.
    - In Chippies Field, the changes in soil-P levels were not significant as a result of the fertiliser type but there was an indication that biosolids tended to increase soil extractable-P.
    - In both sites, soil-P index remained close to constant.
- The analyses of soil extractable-K conducted in Avenue Field showed an effect of the crop and also the fertiliser type on soil-K status. Soil-K levels in post-harvest of the 2nd wheat (2008) were approximately close to the initial level (211 mg [K] kg^{-1}). However, after 2 years of grass, K-index decreased from 3 to 2+.
- The analyses of heavy metals in soil (Cd, Cu, Zn, and Pb) did not show significant changes in their levels compared with those recorded at the start of the experiment in Avenue Field.
- Overall, soil pH remained unchanged despite some temporary changes recorded possibly related to the timing of sampling.
- SOM levels were not affected by the fertiliser type used; however, there was an effect of the crop in increasing SOM levels, including the unfertilised control soil, following the establishment of grass in Avenue Field in 2009.

CHAPTER 8

ECONOMIC ANALYSIS OF THE CROP RESPONSES TO APPLIED NITROGEN – APPROACH TO DETERMINING THE ACCEPTABLE PRICE OF ORGANOMINERAL FERTILISERS

8 ECONOMIC ANALYSIS OF THE CROP RESPONSES TO APPLIED NITROGEN – APPROACH TO DETERMINING THE ACCEPTABLE PRICE OF ORGANOMINERAL FERTILISERS

8.1 Introduction

There are a number of issues related to the economics of fertiliser application to crop production; these include the response of the crop to applied nutrients, the fertiliser price, and also its relationship with the price of the crop (Melgar and Muñoz, 2008). The response of the crop is usually measured with regards to the increase in crop yield from the application of fertiliser. The crop response data generated from the field studies at the College Farm, Silsoe (**Chapter 7**) needs to be complemented by an economic analysis. This analysis should reflect the economic benefits of the use of organomineral fertilisers in crop production in comparison with standard mineral fertilisers and biosolids.

The ultimate success in the adoption of a new technology is dependent on whether it is able to provide a greater economic result to farmers than current practices. This could come from increased crop yield and/or reduced input costs (James, 2000) including the costs associated with the use of fertilisers. James (2000) addressed the question of whether variable rate application of nitrogen fertiliser was economically advantageous compared with uniform application strategies. A similar question can be formulated in the context of the present work and it is whether the use of organomineral fertilisers for winter wheat and rye grass production is more profitable than the use of biosolids or standard mineral fertilisers. As the OMF products considered in this research are new to both United Utilities plc and the potential fertiliser market, it is essential that attempts are made to estimate an acceptable price for OMF to both the producers and users of the product.

This chapter focuses on the economic analysis of the crop responses to applied fertiliser reported in **Chapter 7**. Special emphasis was placed on the effect of the use of OMF and urea upon crop's gross margins. The objectives of this chapter are summarised below:

- To determine the most economic rates of nitrogen (MERN) and their corresponding crop yields (Y_{MERN}) based on the approach used in previous investigations on the subject (Godwin et al., 1999; James, 2000; James and Godwin, 2003),
- To determine the crop's gross margins based on the MERN and Y_{MERN} analyses,

- To investigate fertiliser prices (1994-2010) and their trends (2010-2015) by means of linear regression analysis,
- To conduct sensitivity analyses to be able to determine changes in the crop's gross margins as a result of changes in the price of nitrogen fertiliser and fluctuations below and above the constant price of the grain as well as the yield of the crop,
- To present the results of a pilot choice experiment which was conducted to investigate the farmers' acceptance for OMF, and
- To present a methodological approach to determining the farmers' willingness to pay for OMF. The approach presented will provide a platform for future research into the subject.

The method suggested for estimating the farmers' willingness to pay (WTP) for OMF is based on research conducted by Pegurara-Gasparin (2009) who studied the acceptance of on-farm automated traceability systems (Peets et al., 2008; Peets, 2009).

The economic analysis of the crop responses to applied nitrogen fertilisers was based on the results obtained for winter wheat reported in **Chapter 7**. The conduct of such analysis for grassland production systems appeared to be significantly more complex as it requires knowledge of the grass-energy needed in relation to stocking rates, supplementary feed inputs, target yields, cutting and grazing regimes, and production system; e.g. milk, meat or other (Fisher and Jewkes, 2009). In this respect, Fisher and Jewkes (2009) developed an integrated approach which aims at providing recommendations of nitrogen applications specifically for grass-based systems and it considers the physical response to applied fertiliser as well as the energy requirements on-farm. However, the investigation conducted on the responses of the grass crop to the application of organomineral fertilisers provided the basis to be able to undertake such analyses which may be addressed in future work.

8.2 Grain and fertiliser prices

8.2.1 Brief overview of the global and the UK contexts

The recent period after the recession of 2008-09 saw the global economy recovering at a faster rate than the projections made during the crisis. In fact, recent estimates by the IMF indicated that world output is expected to grow by *c*.4.2-4.3% between 2010 and 2011 following the 0.6% decline observed in 2009 (Heffer and Prud'homme, 2010).

Following this recession, the focus has been on the reduction of public debt and it is expected that the efficacy of the measures taken will inevitably affect both confidence and growth in the next few years, especially in Europe (Heffer and Prud'homme, 2010). The present economic and financial contexts will affect fertiliser demand in various ways. While a possible return to stability in the price of commodities will provide a less risky ground for growers to continue purchasing fertilisers and will push up the demand, mainly for P and K, some turbulence in the financial market could result in more speculation in agricultural commodities. In addition, crude oil prices are expected to stay firm hence providing some incentive for production of biofuels. At a global level, much attention has been paid to the recovery of the economy and also climate change and to a lesser extent on food security (Heffer and Prud'homme, 2010). However, in the UK, the recently launched Food Strategy 2030 (Defra, 2010) which was drawn upon a previous report by the Cabinet Office (2008) has brought back on the agenda a number of issues regarding food security such as the need for increasing food production in a sustainable manner. In this context, it is difficult to dissociate the need to increase food production without increasing the use of fertilisers which could bring about increments in their price. World estimates of cereal production (FAO, 2010; Archer, 2010) indicated that an increase of *c*.2% could be expected in 2010-11 with respect to 2009 which is approximately equivalent to the projected increase in cereals' utilisation in the same period for which global inventories should not change significantly. This has been reflected on the international cereal prices which have remained fairly stable but higher than the pre-crisis levels (Heffer and Prud'homme, 2010).

The UK wheat price follows international grain prices (Archer, 2010). The mean value of wheat (feed) in the UK, as reported by Nix (1994-2010), was 90 £ t^{-1} [grain]. The data shown in **Figure 8.1**, derived from Nix (1994-2010) shows the annual change in a budgeted value for wheat and does not include the full range of price changes that might have occurred in the price series during that period. For example, LIFFE (London International Financial Futures & Options Exchange) wheat (feed) price for March 2011 was £205 per tonne (HGCA, 2011). The occurrence of such extreme prices is not highlighted in the dataset for the period analysed. The use of this data (Nix, 1994-2010) is justified since the gross margin analyses conducted in **Section 8.3** were undertaken using mean annual prices/costs and there was a need to be consistent with the information presented. More detailed price information can be found in HGCA (2011). The decline in the price of wheat observed prior to 2000 responded mainly to the Pound being a strong currency which meant that the export market became difficult to enter and it was aggravated by the oversupply of grain from Eastern Europe and the US where removal of some financial support resulted in increased production (James, 2000).

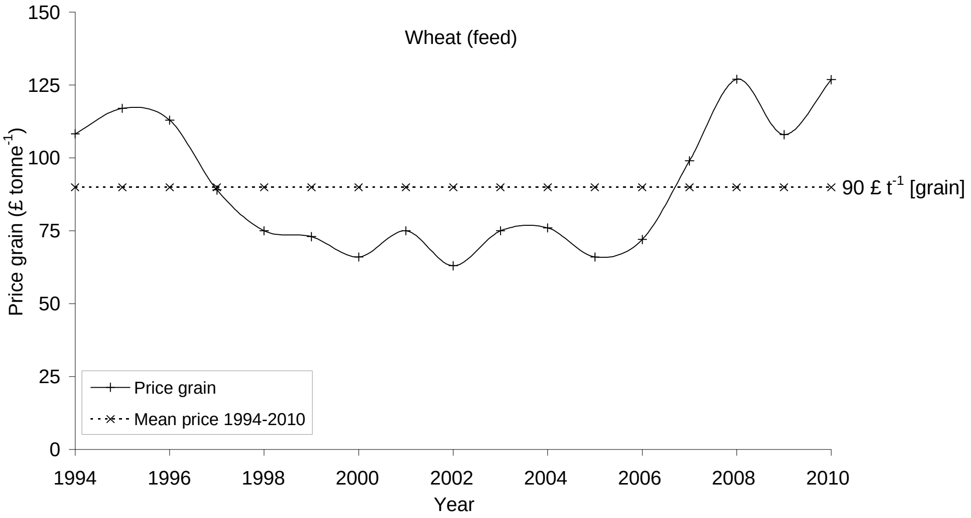


Figure 8.1: Mean annual realised (producer) price of wheat (feed) in the UK and mean price for the period 1994-2010 (source: Nix, 1994-2010).

This process was also accelerated by the increasing purchase power of supermarkets which contributed to drive down the price of agricultural products (James, 2000). The increase in the price of wheat observed from 2005-06 could continue to rise in response to the projected increase in the demand for grain used for biofuels. This includes wheat whose demand is forecasted to increase from *c*.3 million tonnes as recorded for 2006-2009 to *c*.7 million tonnes in 2013-2015 (Archer, 2010). The overall decline in the price of grain prior to this period was, to certain extent, accompanied by a decrease in the price of nitrogen fertilisers since supply rapidly surpassed demand. However, low fertiliser prices could not be sustained in the following years since production costs remained high/increased in response to the increment recorded in the price of natural gas (James, 2000; Brentnall, 2008). Later, a sharp increase in the cost of the fertiliser in 2008, which was also the case in the UK, significantly reduced expenditure on agricultural inputs. The demand for nitrogen fertiliser is relatively inelastic for which the reduction in fertiliser inputs was at expense of reduced application of P (by *c*.11%) and K (by *c*.20%) as reported by Heffer and Prud'homme (2010). Overall, the demand for N, P and K is forecasted to increase at a rate of 2.5% per year (*c*.2% for N alone) to 2014-15 (Heffer and Prud'homme, 2010) which could drive prices upwards. The expected increase in demand may be counterbalanced by potential surpluses originated as a result of increased production capacity in the main producing countries (Prince et al., 2009; Heffer and Prud'homme, 2010). However, it has also been indicated (Brentnall, 2008) that the fertiliser industry is moving into a period of sustained tight supply.

Brentnall (2008) also highlighted that developments in the nitrogen sector are mainly driven by feedstock availability and price. In this respect, new infrastructure and investment in liquefied natural gas provided a strong competition for the feedstock sector including finance and equipment supply. This resulted in increased construction costs which restricted the expansion of production capacity even at high international product prices. In addition, agricultural expansion in South America and other parts of the developing world, including fast developing economies (e.g. BRIC – Brazil, Russia, India and China), could also contribute to increase the demand for nitrogen fertilisers, and providing supply was not fed from local (new) capacity, prices could move upwards as a result. It is also envisaged that demand can increase as a result of the enforcement of legislation concerning biofuels in the EU (Brentnall, 2008). Hence, the supply-demand relationship may remain unstable exerting pressure on the price of nitrogen fertilisers. Despite energy prices being well below the records of 2008, they have increased during 2009-10 and could potentially force an increase in the price of nitrogen. Heffer and Prud'homme (2010) highlighted that in the short-term however no significant changes in energy prices may be expected; although the increments in price observed more recently show that this projection may be erroneous.

8.2.2 Nitrogen fertiliser

The fertiliser prices previously shown in **Section 2.3.1** were reviewed for the period between 1994 and 2010 and they are presented in **Figure 8.2** for both ammonium nitrate- and urea-N. The price of a typical NPK fertiliser (20:10:10) is also shown so as to provide a reference for comparison with OMF which are of similar nature in terms of their nutrients composition (**Figures 8.3**). The regression analyses undertaken allowed projecting the price of the nitrogen and the NPK fertilisers to 2015 which appears to be in line with the timescale for OMF development. Projections beyond this point in time, although possible, may not be sufficiently reliable; the effect being shown by the 95% confidence intervals fitted to the linear model.

These analyses were first undertaken including the full price dataset (1994-2010) and subsequently after removing the data corresponding to 2008 which appeared to be the result of an economic conjuncture instead of the true reflection of a trend. However, the use of the full price dataset (1994-2010) provides a better indication of the natural volatility in the fertiliser (and energy) prices. Therefore, it is reasonable to state that, in order to account for this volatility, economic analyses should be conducted considering not only the projected price of the fertiliser using the full price dataset available (1994-2010) but also the upper 95% confidence interval of the regression analysis.

The linear regression analyses showed in general acceptable fits, as indicated by the R^2 and the p-values encountered, especially when the data corresponding to 2008 were removed from the dataset. Exponential relationships between the fertiliser price and the time are also possible but they were, however, not applied. The linear models fitted were considered to be simpler and provided a more cautious approach to describing these relationships. The combined effect of the decline in the price of the grain prior to 2006-07 and the progressive increase in the cost of nitrogen has been reflected on reduced crop margins in that period. It appears therefore that there may be an opportunity for OMF products to increase profit margins by means of reduced input costs of fertilisers.

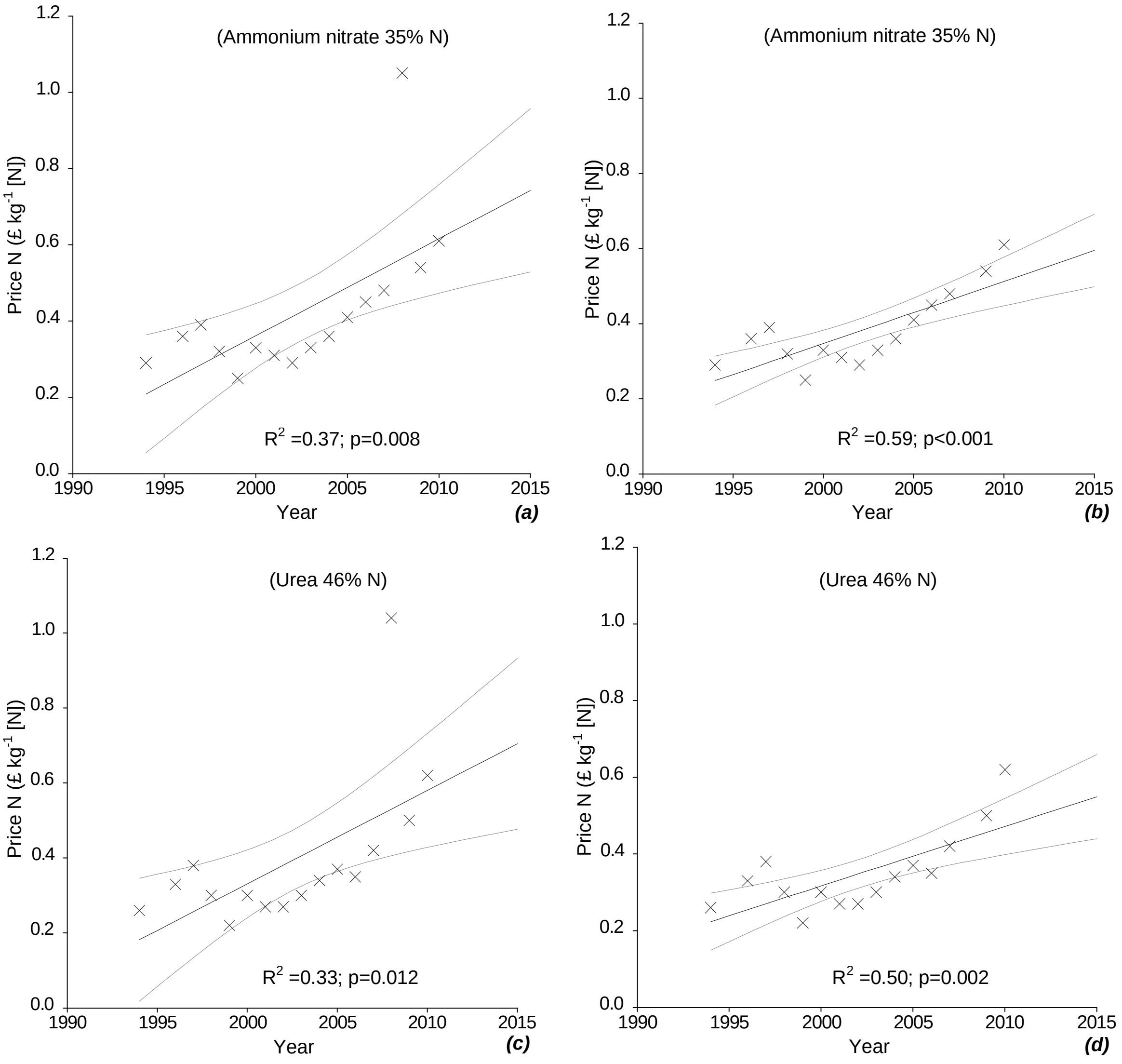


Figure 8.2: (*a*, *b*) Price of ammonium nitrate-N and (*c*, *d*) urea-N for the period 1994-2010 in the UK (source: Nix, 1994-2010) and predicted price to 2015 based on the price-series for the same period. Notice that in (*b*) and (*d*) the data corresponding to 2008 were removed from the dataset. The two curves on both sides of the fitted line represent its 95% confidence interval.

The regression analyses indicated that, assuming that the recent price trend continues, the price of straight nitrogen fertilisers is expected to increase (see also **Table 8.1**) which is in close agreement with some of the projections made, as highlighted earlier in **Section 8.2.1** (e.g. Brentnall, 2008; Prince et al., 2009; Heffer and Prud'homme, 2010). This was more evident when 2008's prices were included in the analyses; in fact, the expected prices of nitrogen by 2015, as predicted by the regression analyses in **Figures 8.2b-d**, are below current (2010) prices and they are only exceeded by the prices corresponding to the upper 95% confidence interval.

As can be seen in **Figure 8.2**, the price of nitrogen increased significantly from *c*.0.25 £ kg^{-1} [N] in 1994 to *c*.0.60 £ kg^{-1} [N] in 2010 for both urea- and ammonium nitrate-N respectively. The prices of the nitrogen fertiliser shown in **Figure 8.2c** for the years 2007-2010 were used as a basis for the calculation of the crop's gross margins which are studied later in **Section 8.3**. The analysis of the data corresponding to a typical NPK compound fertiliser (20:10:10) showed a similar trend to that observed for nitrogen (**Figure 8.3**). The price of 20:10:10 also increased substantially from 110 £ t^{-1} in 1994 to 255 £ t^{-1} in 2010 which was in line with the overall increase recorded for straight nitrogen fertilisers. The price of triple super-phosphate (TSP) increased from 100 £ t^{-1} in 1994 to 315 £ t^{-1} in 2010 but it peaked 690 £ t^{-1} in 2008 (Nix, 1994-2010).

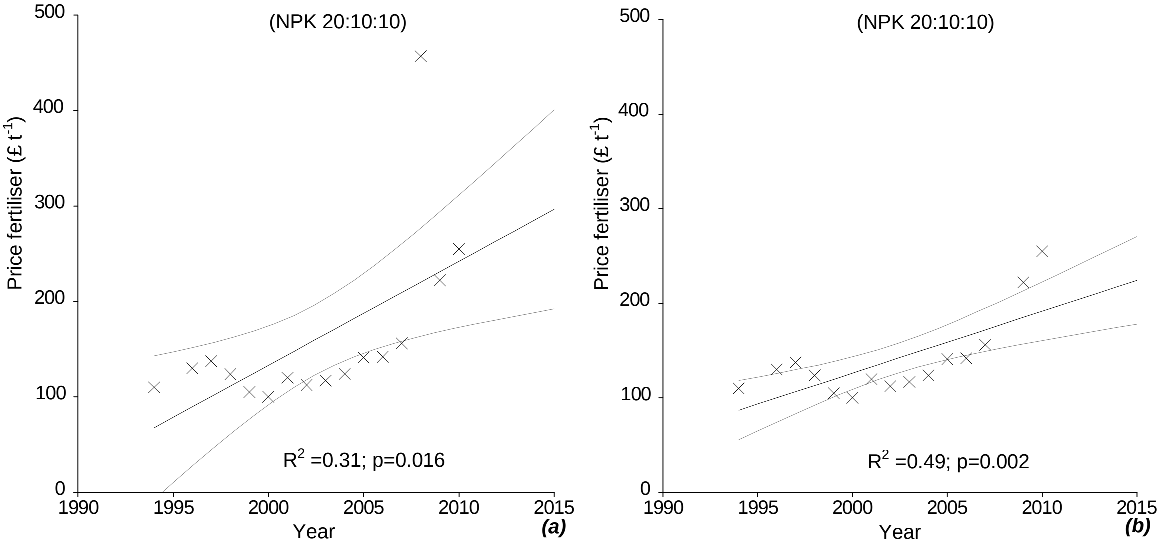


Figure 8.3: Price of an NPK fertiliser (20:10:10) for the period 1994-2010 in the UK (source: Nix, 1994-2010) and predicted price to 2015. Notice that in *(b)* the price corresponding to 2008 was removed from the dataset. The two curves on both sides of the fitted line represent its 95% confidence interval.

The same observation made for straight nitrogen fertilisers can be indicated for 20:10:10. The analysis shows that the projected price in 2015 will be above the current (2010) price of NPK when the full price dataset was included in the trend. In **Figure 8.3b**, the price of NPK recorded in 2010 is approximately equivalent to the price corresponding to the upper 95% confidence interval in 2015. Based on the information shown in **Figures 8.2** & **8.3**, a summary of the fertiliser prices is given in **Table 8.1**. This includes the prices recorded in 2010 and the expected prices in 2015 which were also expressed in percentage of 2010's prices (ΔP, %). The 2015's prices corresponding to the ±95% confidence interval are also quoted to provide an indication of the expected variability in the trend.

Table 8.1: Current (2010) and expected fertiliser prices in 2015. The ±95% indicates the fertiliser prices for 2015 corresponding to the confidence intervals shown in the regression analyses (Figures 8.2 & 8.3). [ΔP: % change in the price in 2015 compared with 2010].

Fertiliser		**--- Full dataset (1994-2010) ---**				**----- Excluding 2008's data -----**			
type	**2010**	**2015**	**ΔP (%)**	**+95%**	**-95%**	**2015**	**ΔP (%)**	**+95%**	**-95%**
Urea (£ kg^{-1} [N])	0.62	**0.70**	16.7	**0.90**	0.50	**0.55**	-12.7	**0.67**	0.48
(*)AN (£ kg^{-1} [N])	0.61	**0.74**	21.3	**0.94**	0.56	**0.60**	-1.6	**0.70**	0.50
20:10:10 (£ t^{-1} [NPK])	255	**295**	15.7	**395**	185	**225**	-13.3	**270**	180

(*) AN: ammonium nitrate.

As can be read off the table, there are large differences in the expected 2015's fertiliser prices depending whether the data corresponding to 2008 is/not included in the analysis. It can be stated that a more realistic estimation of fertiliser prices is made when the full price dataset (1994-2010) is considered in the analysis. In this respect, there is not enough evidence to suggest that fertiliser prices in 2015 will be below the prices observed in 2010; on the contrary, prices have increased continuously since 2000.

A discussion on gross margins' and gross margins' sensitivity to grain value and nitrogen price is presented in the following section (**Section 8.3**). This investigates how changes in the price of the grain and nitrogen fertiliser affect crop's gross margin when OMF is used in crop production in comparison with biosolids and urea. This analysis is based on the experimental results obtained from the field studies at the College Farm (Silsoe) and it uses a similar approach to that reported in the work undertaken by James (2000). The analysis was conducted to provide a broad indication on how gross margins can be affected by a particular fertiliser choice. At a later stage, this work can be taken forward to produce more detailed economic analyses which may be required to investigate how the fertiliser choice can affect the profitability of specific farming/production systems.

8.3 Gross margins

Gross margin (GM) is expressed as the difference between gross income (GI) and total variable costs (TVC). Gross income is given by the yield of the crop multiplied by its market price. The main components of the variable costs are seeds, fertilisers, agrochemicals, and casual and contract work (Nix, 2010). In order to facilitate comparisons of the results obtained for the various fertiliser types used, the yield of the crop corresponding to the most economic application rate of nitrogen (MERN) was used as basis for the calculation of the gross income. This was possible since the response curves for each fertiliser type were available (**Chapter 7**) which allowed the MERN and its corresponding crop yield ($\mathrm{Y_{MERN}}$) to be calculated for a range of price ratios; i.e. the ratio price of nitrogen to price of crop as shown in **Equation [8.6]**. These relationships are represented by the following:

$$GM\left(£\ \ ha^{-1}\right) = GI\left(£\ \ ha^{-1}\right) - TVC\left(£\ \ ha^{-1}\right) \qquad \textbf{[8.1]}$$

Where:

- GM: gross margin of the crop;
- GI: gross income;
- TVC: total variable costs.

And,

$$GI\left(£\ \ ha^{-1}\right) = Y_{MERN}\left(kg\ \ ha^{-1}\right) \times P_C\left(£\ \ kg^{-1}\right) \qquad \textbf{[8.2]}$$

Where:

- Y_{MERN} : crop yield correspondent to MERN;
- P_C : price of the crop (average price for the year of harvest).

And,

$$TVC\left(£\ \ ha^{-1}\right) = \sum Variable\ \ Costs\left(S, F, A, C\right) \qquad \textbf{[8.3]}$$

Where:

- *S*: cost of seeds;
- *F*: cost of fertilisers;
- *A*: cost of agrochemicals; i.e. herbicides, fungicides, insecticides, growth regulators;
- *C*: cost of casual and contract work.

It is important to note that gross margin is not equivalent to profit since fixed costs such as rent, labour, machinery and general overheads, still need to be accounted for before a profit is made (Nix, 2010).

In addition, gross margins are year specific as a result of changes that may occur in both the price and the yield of the crop, and also because variable costs may be different year on year (Nix, 2010). In general, with regards to the costs' calculation, the use of a farmer's own equipment and labour is considered to be a fixed cost whereas the employment of contractors is usually regarded as a variable cost (Nix, 2010).

The usefulness of gross margins is that they provide a valuable indicator of the technical-economic efficiency achieved and allow comparisons to be made when changes in the use of inputs are introduced. For the purpose of this work, to be able to compare the effects of the use of a particular fertiliser type on the resultant gross margin of the crop, the economic analysis was conducted by deducting the cost of the fertiliser to the gross income. Therefore, GM as defined in **Equation [8.1]** can be expressed in the form shown in **Equation [8.4]** as suggested by James (2000):

$$GM\left(\pounds\ ha^{-1}\right) = GI\left(\pounds\ ha^{-1}\right) - C_F\left(\pounds\ ha^{-1}\right) \qquad \textbf{[8.4]}$$

Where:

- GM: gross margin of the crop;
- GI: gross income of the crop as defined in **Equation [8.2]**;
- C_F: cost of the fertiliser;

The calculation of gross margins in the form shown in **Equation [8.4]** implies that all other variable costs are identical regardless of the fertiliser type used. However, this is not exactly true since the cost of spreading varies in relation to the concentration of nitrogen in the product and the nitrogen rate applied which need to be accounted for as they are directly associated with the practice of fertilisation. Therefore, C_F can be defined to include the cost of fertiliser spreading in addition to the unit price of nitrogen and the rate used as shown in **Equation [8.5]**:

$$C_F\left(\pounds\ ha^{-1}\right) = C_S\left(\pounds\ ha^{-1}\right) + \left\{P_N\left(\pounds\ kg^{-1}\right) \times MERN\left(kg\ ha^{-1}\right)\right\} \qquad \textbf{[8.5]}$$

Where:

- C_S: cost of spreading;
- P_N: price of nitrogen;
- MERN: the most economic application rate of nitrogen.

To be able to obtain the most economic rates of nitrogen (MERN), an estimation of the price ratios (R_P) was required which were calculated in the form shown in **Equation [8.6]** following the procedure reported in earlier work (Kachanoski et al., 1996; James and Godwin, 2003).

$$R_P = \frac{P_N}{P_C} \tag{8.6}$$

Where:

- P_N: price of nitrogen (£ kg^{-1} [N]);
- P_C: price of the crop (£ kg^{-1} [grain]).

The R_P is simply the breakeven ratio and indicates the extra return of the produce that just covers the extra unit of nitrogen added. The R_P values were also calculated for the complete dataset of grain (**Figure 8.1**) and nitrogen prices (**Figure 8.2**) and linear regression analyses were conducted to make projections to 2015 (**Figure 8.4**). Similarly, the R_P values were first regressed including the complete dataset (1994-2010) and subsequently after removing 2008's data which clearly reflected an economic conjuncture rather than the real trend. This effect is shown by the R^2 values encountered and also by the 95% confidence intervals fitted to the linear model.

The regression analyses indicated that R_P is set to increase which means that, in the future, the MERN would have to be reduced accordingly and consequently both Y_{MERN} and the resultant gross margin of the crop may be lower. The R_P values for 2015 are expected to be *c*.7.40 (range of 5.95 to 8.75 for the ±95% confidence interval – **Figure 8.4a**) and *c*.6.87 (range of 5.75 to 8.10 for the ±95% confidence interval – **Figure 8.4c**) for ammonium nitrate- and urea-N respectively. The increase in R_P recorded between 1994 and 2010 from 2.64 to 4.84 for ammonium nitrate-N and from 2.41 to 4.92 for urea-N clearly reflects a faster increase in the price of nitrogen with respect to the price of the grain. The R_P values in 2010 also indicated the need to produce approximately double the amount of grain for every kg of nitrogen used compared to that requiered in 1994 in order to break-even.

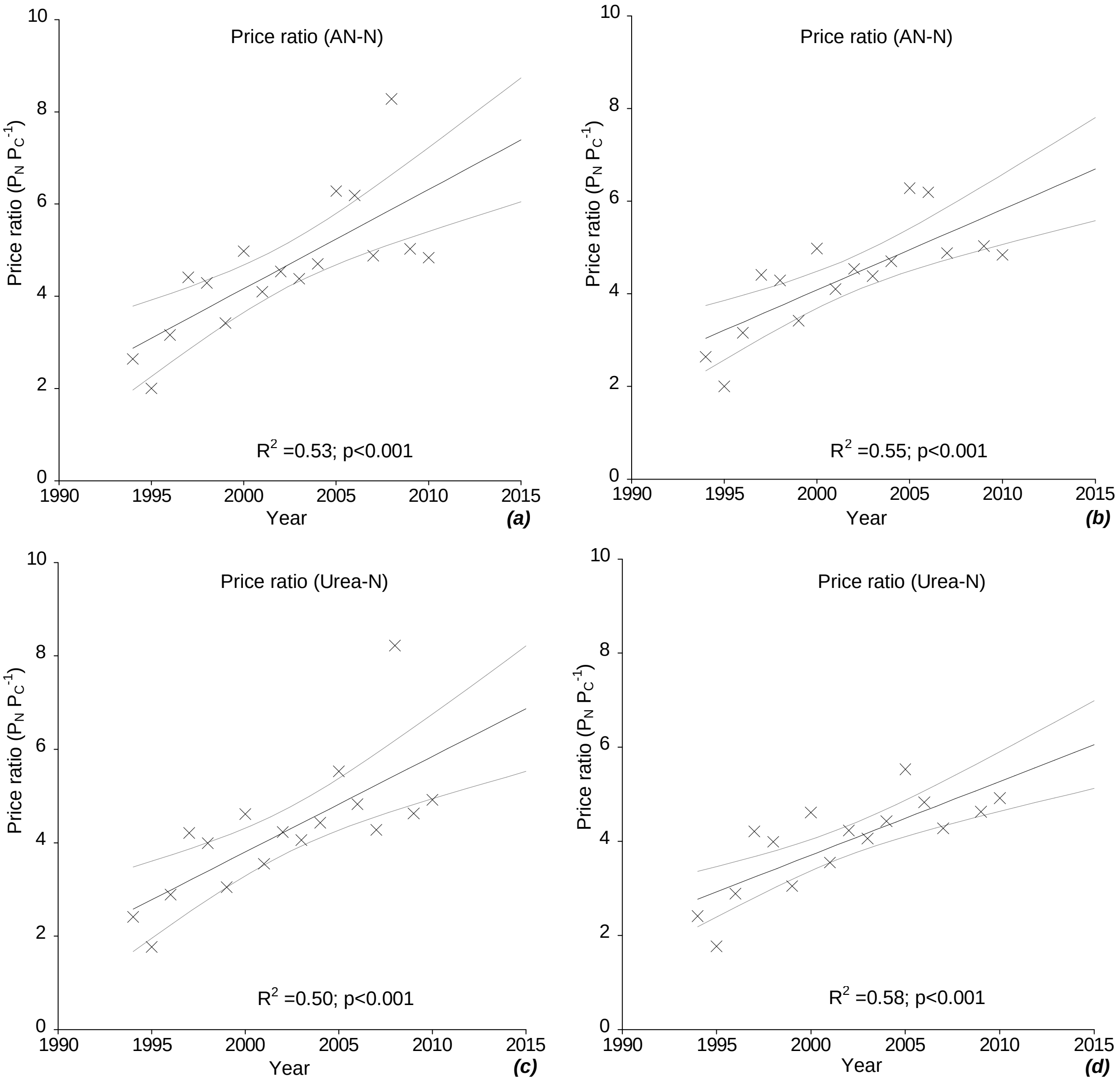


Figure 8.4: (*a, b*) Price ratios for N-ammonium nitrate and (*c, d*) for N-urea for the period 1994-2010 and predicted values to 2015. Notice that in (*b, d*) the data corresponding to 2008 were removed from the dataset. The two curves on both sides of the fitted line represent its 95% confidence interval.

Following the work of James and Godwin (2003), the MERN can be determined when the differential, taken from the quadratic equations that describe the response of the crop to nitrogen application (**Equation [8.7]**), is equated to R_P (**Equation [8.8]**). The actual equations obtained for winter wheat in the field studies were reported in **Chapter 7**.

Given,

$$y = a + bx - cx^2 \qquad \textbf{[8.7]}$$

Where:

- y: yield of the crop (kg ha^{-1});
- x: nitrogen application rate (kg [N] ha^{-1});
- a, b, c: regression coefficients.

Therefore,

$$\frac{dy}{dx} = b - 2cx' = R_P \qquad \textbf{[8.8]}$$

Then,

$$MERN = \frac{b - R_P}{2c} \qquad \textbf{[8.9]}$$

The yield (Y_{MERN}) corresponding to the MERN was calculated by replacing the actual value of MERN by "x" on the response function **[Equation 8.7]** and solving the equation. The importance of the MERN is that at this point, the economic return from the nitrogen applied is maximised. A summary of the MERN and the corresponding Y_{MERN} are shown in **Table 8.2** which were used for the calculation of gross margins for winter wheat for the years 2006-07 to 2009-10 (see later **Table 8.5**). The values of MERN that are well above 250 kg [N] ha^{-1} should be treated with caution as they may not truly reflect a real situation. These were due to the yield to nitrogen response curve for that particular year.

Table 8.2: MERN (kg [N] ha^{-1}) and Y_{MERN} (kg [grain] ha^{-1}) obtained for winter wheat (2006-07 to 2009-10) for the four fertiliser types used in the trials. [Assumes: MERN obtained for P_N =$P_{N\text{-}Urea}$ except for biosolids where $P_{N\text{-}Biosolids}$ =0 therefore MERN =N_{max} and Y_{MERN}= Y_{max}; *SD*: standard deviation].

Fertiliser/	**P_N**	**$^{(*)}$Biosolids**		**OMF_{10}**		**OMF_{15}**		**Urea**	
Year	**£ kg^{-1}**	**MERN**	**Y_{MERN}**	**MERN**	**Y_{MERN}**	**MERN**	**Y_{MERN}**	**MERN**	**Y_{MERN}**
2006-07	0.42	235.9	10734	274.1	10707	248.3	10765	226.9	10992
2007-08	1.04	302.3	7418	165.9	8052	190.3	7591	197.7	9525
2008-09	0.50	181.7	9716	222.2	10542	213.1	12372	220.4	12925
2009-10	0.62	266.9	3761	367.7	7083	342.7	7222	256.8	7947
Mean	**0.65**	**246.7**	**7907.8**	**257.5**	**9095.8**	**248.6**	**9487.5**	**225.4**	**10347**
SD	**0.28**	**51.13**	**3092.4**	**85.74**	**1810.3**	**67.12**	**2495.7**	**24.36**	**2121.1**

$^{(*)}$ Values of MERN and Y_{MERN} are equivalent to the N_{max} and Y_{max} values reported earlier in **Table 7.4a**.

Gross margins were estimated using **Equation [8.4]** and details of their calculation are provided in **Appendix A.8.1.** The calculation of the MERN assumed for all the years that the price of OMF-N was equivalent to the price urea-N except for biosolids-N which was considered to be zero.

Hence, the MERN and the Y_{MERN} for biosolids are equivalent to the N_{max} and the Y_{max} respectively. In order to simplify the analysis, the cost of the nitrogen, applied in 2006-07 in the form of UAN (33% N – solution) at a rate of 100 kg [N] ha^{-1}, was added to the cost of the nitrogen corresponding to the MERN. This allowed the cost of nitrogen to be estimated using a single nitrogen price for all treatments in that particular year. The calculation of the spreading costs required the conversion of the nitrogen application rates as given by the MERN (kg [N] ha^{-1}) to kg [product] ha^{-1} since the amount charged per hectare depends on the quantity of product applied. This conversion was done based on the nitrogen concentration of the products which was reported in **Chapter 3**. The cost of broadcast spreading at the contract charge and farmer's cost is shown in **Table 8.3** (from Nix, 2007-10):

Table 8.3: Contract charge and farmer's cost of broadcast spreading (£ ha^{-1}) between 2006-07 and 2009-10 (source: Nix, 2007-10).

Broadcast spreading range (kg ha^{-1})	**2006-07**		**2007-08**		**2008-09**		**2009-10**	
	Cont'r	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**
	£ ha^{-1}							
125-375	10.25	6.40	10.10	7.80	10.25	7.30	9.75	7.80
500-750	16.16	10.10	16.32	12.60	16.29	11.60	15.63	12.50
1000-1250	24.32	15.20	24.61	19.00	24.43	17.40	23.50	18.80

The following example shows the calculation of the cost of spreading of OMF_{15} for 2009-10:

Given,

$MERN = 342.7\ kg\ [N]\ ha^{-1}$, and

$N\ concentration\ in\ OMF_{15} = 11.39\%\ N$

The amount of OMF_{15}, as product, required to achieve the MERN is equivalent to 3008 kg [OMF_{15}] ha^{-1}. Assuming that the full rate is split into two dressings carrying 50% of the total rate each, the rate of OMF_{15} required per dressing is therefore equivalent to 1504 kg [product] ha^{-1}. This quantity was outside the ranges given in **Table 8.3** (1000-1250 kg ha^{-1}); therefore, the cost of spreading had to be estimated. This was done as follow:

$$\frac{1504\ kg\ [OMF_{15}]\ ha^{-1}}{1250\ (kg\ ha^{-1})} = 1.2 \text{ [application equivalent per dressing]} \qquad \textbf{[8.10]}$$

As highlighted above, the MERN was split into two dressings; therefore, the full rate requires the equivalent to 2.4 applications. The estimated cost of spreading at contractors' charge is:

$$2.4 \ applications \ \times \ 23.50 \ (£ \ ha^{-1}) = 56.40 \ (£ \ ha^{-1}) \qquad \textbf{[8.11]}$$

And, the estimated cost of spreading at farmer's cost is:

$$2.4 \ applications \ \times \ 18.80 \ (£ \ ha^{-1}) = 45.12 \ (£ \ ha^{-1}) \qquad \textbf{[8.12]}$$

This procedure was repeated for the estimation of the cost of spreading for each of the fertiliser types applied year on year. A summary of the costs of spreading thereby calculated are shown in **Table 8.4**. The cost of spreading was subsequently deducted from the gross income for the calculation of gross margins (**Table 8.5**).

Table 8.4: Cost of broadcast spreading (£ ha^{-1}) for the four fertiliser types used in the trials for the period 2006-07 to 2009-10. [Assumption: N is applied at MERN and the full N rate is split into two dressings carrying 50% of the total rate each].

Fertiliser	**Biosolids**		**OMF$_{10}$**		**OMF$_{15}$**		**Urea**	
Mean N (%)	**[4.47%]**		**[8.91%]**		**[12.81%]**		**[46.0%]**	
Year	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**
2006-07	118.00	73.74	65.60	41.00	49.14	30.72	20.50	12.80
2007-08	131.36	101.43	34.32	26.49	32.64	25.20	20.20	15.60
2008-09	89.45	63.71	48.86	34.80	33.15	23.61	20.50	14.60
2009-10	91.56	73.25	96.68	77.35	56.40	45.12	19.50	15.60
Mean	**107.60**	**78.03**	**61.37**	**44.91**	**42.88**	**31.20**	**20.18**	**14.65**
SD	**20.49**	**16.27**	**26.79**	**22.43**	**11.92**	**9.85**	**0.47**	**1.32**

As can be read off the table, the cost of spreading of biosolids was on average ***c*.5.3** times higher than that of urea whereas for OMF$_{10}$ and OMF$_{15}$ this cost was ***c*.3.0** and ***c*.2.1** times higher than that of urea respectively. In addition, if a contractor was hired, the cost of fertiliser application, and regardless of the fertiliser type, would be ***c*.1.4** times higher than the farmer's average cost of spreading for the same range of tonnage applied per hectare and per year. In order to account for these differences in the cost of spreading, gross margins were calculated for two different scenarios. The first scenario considered using farmer's equipment and labour and the second one assumed employing contractors to conduct the spreading operations.

Although the costs arising from using farmer's own equipment and labour are usually regarded as fixed costs these were included as part of the variable costs to be able to compare both scenarios. The need for contracting out field operations is largely dependent on the size of the enterprise, the availability of equipment and labour, the number of working days (Vozka, 2007; Vozka et al., 2007), and also whether specialised spreading equipment is/not required. On smaller farms (e.g. <250 ha) the employment of contractors to conduct field operations is usually regarded as a cost-effective option whereas medium-sized farms (e.g. up to 750 ha) may require contracting out specific field operations and on larger farms the use of contractors may be a strategy for work optimisation during peak periods (Forristal, 1995; Vozka, 2007). The results of the gross margins' analysis are presented in **Table 8.5**. It is assumed that the OMF-N is priced at the same price of urea-N and that the price of biosolids-N is zero.

Table 8.5: Gross margins (GM) obtained for winter wheat between 2006-07 & 2009-10 based on the MERN and Y_{MERN} (Table 8.1) and the cost of spreading shown in (Table 8.4) for the four fertiliser types used in the trials. Assumes $P_{N-OMF} = P_{N-Urea}$ and $P_{N-Biosolids} = 0$. [GM's figures given in (£ ha^{-1}); *SD*: standard deviation].

Fertiliser/	**$GM_{Biosolids}$**		**GM_{OMF10}**		**GM_{OMF15}**		**GM_{Urea}**	
Year	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**
2006-07	894.68	938.92	828.20	852.80	861.33	879.76	921.52	929.22
2007-08	810.73	840.65	815.18	823.00	732.84	740.28	983.18	987.78
2008-09	959.88	985.62	978.58	992.64	1196.48	1206.02	1265.20	1271.10
2009-10	386.08	404.40	573.45	592.78	646.81	658.13	829.65	833.45
Mean	**762.84**	**792.39**	**798.85**	**815.31**	**859.37**	**871.05**	**999.89**	**1005.39**
SD	**258.49**	**265.63**	**167.57**	**165.76**	**241.41**	**241.33**	**187.79**	**188.22**

In general, the use of biosolids resulted in higher values of MERN and lower Y_{MERN}, or lower MERN but also consistently lower Y_{MERN} than OMF_{10}, OMF_{15} and urea, except for 2006-07. The results for biosolids (2006-07) were largely influenced by the application of UAN (33% N – solution) at a rate of 100 kg [N] ha^{-1} in the first nitrogen dressing. The relatively high performance of biosolids in the first season could have also been influenced by the over-application of biosolids-N as discussed earlier in **Chapter 7**. These effects were subsequently reflected on the higher $GM_{Biosolids}$ obtained in 2006-07 and also 2007-08 compared with both OMF_{10} and OMF_{15}.

However, after four years, the application of biosolids resulted in $GM_{Biosolids}$ being on average 4.7% and 12.7% lower than GM_{OMF10} and GM_{OMF15} respectively, and approximately 31.1% lower than GM_{Urea} when the fertiliser were spread at contractor's charge.

When the fertiliser was spread at the farmer's average cost of spreading $GM_{Biosolids}$ was 2.9% and 9.9% lower than GM_{OMF10} and GM_{OMF15} respectively, and approximately 26.9% lower than GM_{Urea}. In addition, when $P_{N\text{-}OMF}$ was equivalent to $P_{N\text{-}Urea}$, the GM tended to increase, on average, with the use of more concentrated nitrogen products. This effect was also consistent with the values of Y_{MERN} obtained and the need for lower nitrogen application rates as required for Y_{MERN}. The mean MERN value of biosolids obtained over four years, despite being comparable to those of both OMF, was not able to sustain the same level of grain yield as OMF_{10} and OMF_{15}. It is important to emphasise that the MERN for biosolids was equivalent to the N_{max}. Therefore, the possibilities of increasing grain yield and consequently improving the GM with the use of biosolids, by means of larger nitrogen application rates, can be discarded. This was not the case for the OMF where a favourable change in R_P; for example, by reducing the cost of OMF-N, could still allow for a higher MERN; hence, producing both an increased Y_{MERN} and gross margin.

Logically, the price of OMF will be determined by the price of nitrogen. It has been reported (Heffer and Prud'homme, 2010) that in the eventuality of a general increase in the price of fertilisers, the farmer would response by compromising first the use of P- and K-fertilisers at the expense of nitrogen. This effect has also been shown in recent surveys which monitor fertiliser usage such as that reported by Defra (2009a). In addition, this reaction is more evident when fertilisers are applied on soils having already satisfactory P and K levels or situations where they are required as a strategy to maintain soil fertility. This behaviour has also been shown by the results of a pilot choice experiment which was conducted to investigate the farmers' acceptance of OMF (see later **Section 8.6**).

The gross margins reported in **Table 8.5** which considered the price of OMF-N equivalent to the price of urea-N clearly showed that such price levels are not sustainable and that they resulted in the mean gross margins of OMF_{10} and OMF_{15} being *c*.23-25% and 15-16% lower than the mean GM_{Urea} respectively depending on whether spreading is contacted out or conducted with the farmer's own equipment and labour. These differences can be explained by the resultant R_P values given the price of nitrogen and the impact that such high R_P caused on the calculated MERN.

At high R_P ratios, the MERN needs to be reduced; consequently, crop yield is lower which ultimately has a significant effect on the crop's gross margin. It is understood that the overall lower performance of OMF compared with urea was influenced by the poorer physical and chemical characteristics of the products (see **Chapters 3** and **7**). For urea, and within reasonable limits, a high R_P value has a lesser impact on the crop's gross margin compared with OMF simply because of the higher response curve of urea which means that a higher price of nitrogen can still be affordable.

The results of this gross margins exercise lead to the conclusion that in order to be able to use OMF products profitably, and perhaps most importantly, in order for the farmers to purchase OMF, the expected gross margins of the crop should be of similar level to those achieved with standard nitrogen fertilisers; namely, urea. Therefore, given that the yield response curves of both OMF products are lower than that of urea, an increase in the crop's gross margin may be achieved by a subsidised reduction in the price of nitrogen.

A reduction in P_N will change the R_P ratio which in turn will allow a larger nitrogen rate to be applied and therefore an increase in the expected crop yield (Y_{MERN}). Since an increment in grain yield has a more significant effect on gross margin than any reduction in the cost of nitrogen fertiliser, the resultant is that the crop's gross margin is increased. This is, of course, providing that all other variable costs as well as the price of the crop remained unchanged. The cost of spreading, however, could be higher as a result. This component of the variable costs can be increased if the increment in the nitrogen rate leads to a significant increase in the amount of product applied resulting in increased number of passes with the fertiliser spreader or in the need to hire specialised (and more expensive), spreading equipment. Hence, potential increases in the cost of spreading should be accounted for when estimating gross margins.

An approach is presented to determine the price of OMF nitrogen ($P_{N\text{-}OMF}$) at which the economic result from the use of OMF is similar to that of urea. In order to do this, the crop's gross margins shown in **Table 8.5** for OMF_{10} and OMF_{15} respectively were re-calculated to match ±1% of the GM of the crop obtained with the use of urea and these are shown in **Table 8.6.** The range given by the ±1% of GM_{Urea} is arbitrary as it was difficult to match exactly the results obtained with urea considering the differences in the response curves. Therefore, the $P_{N\text{-}OMF}$ had to be reduced to a point where the MERN resulted in the yield of the crop being sufficiently high to produce a GM of similar order of magnitude (±1%) to that of urea.

In reducing the price of nitrogen, the MERN approaches N_{max} and so does crop yield which tends to approach Y_{max}. When $P_N = 0$, the MERN and Y_{MERN} are equivalent to N_{max} and Y_{max} respectively. The cost of spreading was calculated following the same approach as that used before (**Equations [8.10-12]**) and using the figures shown in **Table 8.3**.

Table 8.6: MERN (kg [N] ha^{-1}), Y_{MERN} (kg [grain] ha^{-1}) and corresponding price of nitrogen (P_N; £ kg^{-1} [N]) for winter wheat (2006-07 to 2009-10) needed for OMF_{10} and OMF_{15} to produce a GM equivalent to ±1% of the GM_{Urea} shown in Table 8.4 except where the value is indicated in *italics* [GM given in £ ha^{-1}; *SD*: standard deviation].

Fertiliser/ Year	**OMF_{10}**					**OMF_{15}**				
	MERN	**Y_{MERN}**	**P_N**	**Cont'r**	**Farmer**	**MERN**	**Y_{MERN}**	**P_N**	**Cont'r**	**Farmer**
2006-07	313.1	10811	0.106	912.18	940.28	268.1	10829	0.212	912.14	932.04
2007-08	201.5	8213	0.104	980.35	989.85	246.6	7823	0.00	*960.09*	*967.71*
2008-09	247.8	10602	0.00	*1095.85*	*1110.00*	221.9	12400	0.200	1260.30	1270.24
2009-10	444.8	7272	0.00	*806.60*	*829.99*	393.2	7371	0.125	822.08	835.06
Mean	**301.8**	**9224.5**	**0.053**	**948.75**	**967.53**	**282.5**	**9605.8**	**0.134**	**988.65**	**1001.26**
SD	**105.8**	**1755.9**	**0.06**	**121.35**	**116.13**	**76.2**	**2413.6**	**0.10**	**189.90**	**187.90**

The values showed in ***italics*** indicate that, for that particular year and treatment, a gross margin comparable (±1% of GM_{Urea}) to that obtained with the use of urea could not be reached even though the N_{max} was applied. In addition, it can be read off the table that for the period analysed, **the mean prices of OMF-N needed to match the required ±1% of GM_{Urea} were *c*.0.05 £ kg^{-1} [N] for OMF_{10} and *c*.0.13 £ kg^{-1} [N] for OMF_{15} compared with *c*.0.65 £ kg^{-1} [N] for urea** in the same period. This means that, **on average, the price of OMF-N should be ≈ $0.1*P_{N-Urea}$ for OMF_{10}, and ≈ $0.2*P_{N-Urea}$ for OMF_{15}**. The purchase of urea in bulk for the production of OMF can help United Utilities plc to reduce the market price of OMF (through reduced input cost of nitrogen); however, it is unlikely that this reduction can be as low as £0.05-0.13 kg^{-1} [N].

The implication of bringing down the price of nitrogen is that the MERN are inevitably increased, on average for OMF_{10} and OMF_{15}, by approximately 75 and 55 kg [N] ha^{-1} respectively above the MERN encountered for urea. This, in turn, can impose a restriction if operating within NVZ as it would require exceeding the field limit for nitrogen application. The cost of spreading OMF at the mean MERN values shown in **Table 8.6** would be approximately 65.58 and 47.70 £ ha^{-1} for OMF_{10}, and 48.40 and 35.20 £ ha^{-1} for OMF_{15} depending whether spreading is contracted out or conducted with farmer's own equipment and labour.

Therefore, the economic result of the farm as a whole should be carefully revised before making a decision regarding the choice of a particular nitrogen fertiliser. The gross margins exercise provides a valuable indication as to what farmers would be prepared to pay for OMF-N. Certainly, the fertiliser choice is to be made not only on the basis of the overall agronomic performance but most importantly on the economic result of the crop rotation and the use of a particular technological package which includes fertilisers. The reduction needed in P_N for OMF to be able to match ±1% of GM_{Urea} can bring about problems in logistics associated with handling larger volumes of materials. This may be dealt with by increasing existing spreading capacity on the farm (but it requires investment) so that work rates are not affected or alternatively by contracting out the spreading operations which was shown to be a more expensive alternative than using the farmer’s own equipment and labour. Maintaining work rates is important considering that at a busy time of the year, the window for application of nitrogen is relatively narrow in terms of availability of good spreading days and could effectively result in more pressure on the farmer to cover the same amount of land. All these factors combined can potentially affect the choice of the fertiliser type for which the advantages of using OMF need to be reflected on the price of the product.

In the following section (**Section 8.4**) a sensitivity analysis was conducted which investigates the changes in the crop’s gross margin as a result of changes in the price of nitrogen and the grain. It provides an indication of the effect that these changes can have on the gross margin of the crop depending upon the fertiliser type used.

8.4 Sensitivity analyses

Sensitivity analyses (**Figure 8.5-8.6**) were conducted which allowed identifying changes in crop’s gross margins as a result of changes in the price of selected components of the variable costs. In order to simplify the analyses, changes in gross margin were investigated with regards to the price of the nitrogen (P_N), the grain (P_C) and the relationship between the two which is expressed by means of the price ratio (R_P). The analyses were conducted for P_C at constant price and also for P_C being ±50% of the constant grain price. The value of the constant price was taken as the mean realised (producer) price of wheat (feed) for the period 1994-2010 (**Figure 8.1**) which was equivalent to 0.09 £ kg^{-1} [grain] as highlighted earlier (Nix, 1994-2010). The minimum and maximum prices of wheat (feed) recorded for the period were 0.063 and 0.127 £ kg^{-1} [grain] in 2002 and 2008 respectively which represented a fluctuation of ±40-45% around the constant price.

Therefore, the range of P_C used (±50% of the constant price) for the sensitivity analyses appeared to be a reasonable and provided a number of representative scenarios. Similarly, the minimum and maximum prices of urea-N were 0.22 and 1.04 £ kg^{-1} [N] in 1999 and 2008 respectively. The range of P_N used in the analyses was 0.2 to 1.2 £ kg^{-1} [N] at regular increments of 0.2 £ kg^{-1} [N] which are in line with the projected increase in P_N and the expected changes in R_P as shown earlier in **Figures 8.2** & **8.4** respectively. The sensitivity analyses (**Figures 8.5-8.6**) showed that, regardless of the fertiliser type used, gross margins are more sensitive to changes in the price of grain (P_C) than the nitrogen (P_N). Taking for example the results obtained for 2006-07 for Avenue Field (**Figure 8.5a**), a 50% increase in P_C; i.e. from 0.090 to 0.135 £ kg^{-1} [grain], resulted in GM_{Urea} being increased by approximately 60% on average for the full range of P_N investigated; whereas, a 50% increase in P_N; i.e. from 0.40 to 0.60 £ kg^{-1} [N], led to a decrease in GM_{Urea} of approximately 4%. It was indicated (**Chapter 7**) that by improving the physical and chemical properties of OMF, their agronomic performance could be significantly enhanced. This is an important aspect which can bring about a significant improvement in the crop's gross margins. The sensitivity analyses also highlight the need to manage the crop efficiently in order to maximise grain yield. In managing the crop, attempts should be made not only to reduce input costs, including nitrogen fertiliser, but also to optimise the use of resources. A greater economic return from the crop may be expected when grain yield is increased as a result of more effective agronomic management.

The analysis shown in the graphs also implies a sensitivity analysis to price ratio (R_P) for the range of nitrogen and grain prices investigated. In this respect, the values of MERN and their correspondent Y_{MERN} had to be re-calculated from the response curves for each price ratio. The spreading costs, in addition to the cost of the nitrogen, were also deducted from the gross income before obtaining these gross margins. Following the discussion concerning the price of OMF-N, it was suggested that it should be reduced to a point where the resultant gross margins of the crop fertilised with OMF were similar (±1%) to those obtained from the crop fertilised with urea. **Figure 8.6-d** which was produced based on the response curves obtained in 2010, shows a worked example using the expected price of urea-N for 2015 according to the regression analyses reported earlier (**Figure 8.4**). The example shows that if $P_{N\text{-Urea}} \approx 0.70$ £ kg^{-1} [N] and $P_C \approx 0.90$ £ kg^{-1} [grain], in order to achieve a similar GM with the use of OMF, $P_{N\text{-OMF}}$ cannot be higher than 0.10 and 0.23 £ kg^{-1} [N] for OMF_{10} and OMF_{15} respectively. As highlighted earlier, in order for OMF to be able to produce an economic benefit comparable to urea, $P_{N\text{-OMF}}$ should be, on average, *c*.0.1*$P_{N\text{-Urea}}$ and *c*.0.2*$P_{N\text{-Urea}}$ for OMF_{10} and OMF_{15} respectively which appears to slightly under-price the value of OMF-N for 2015.

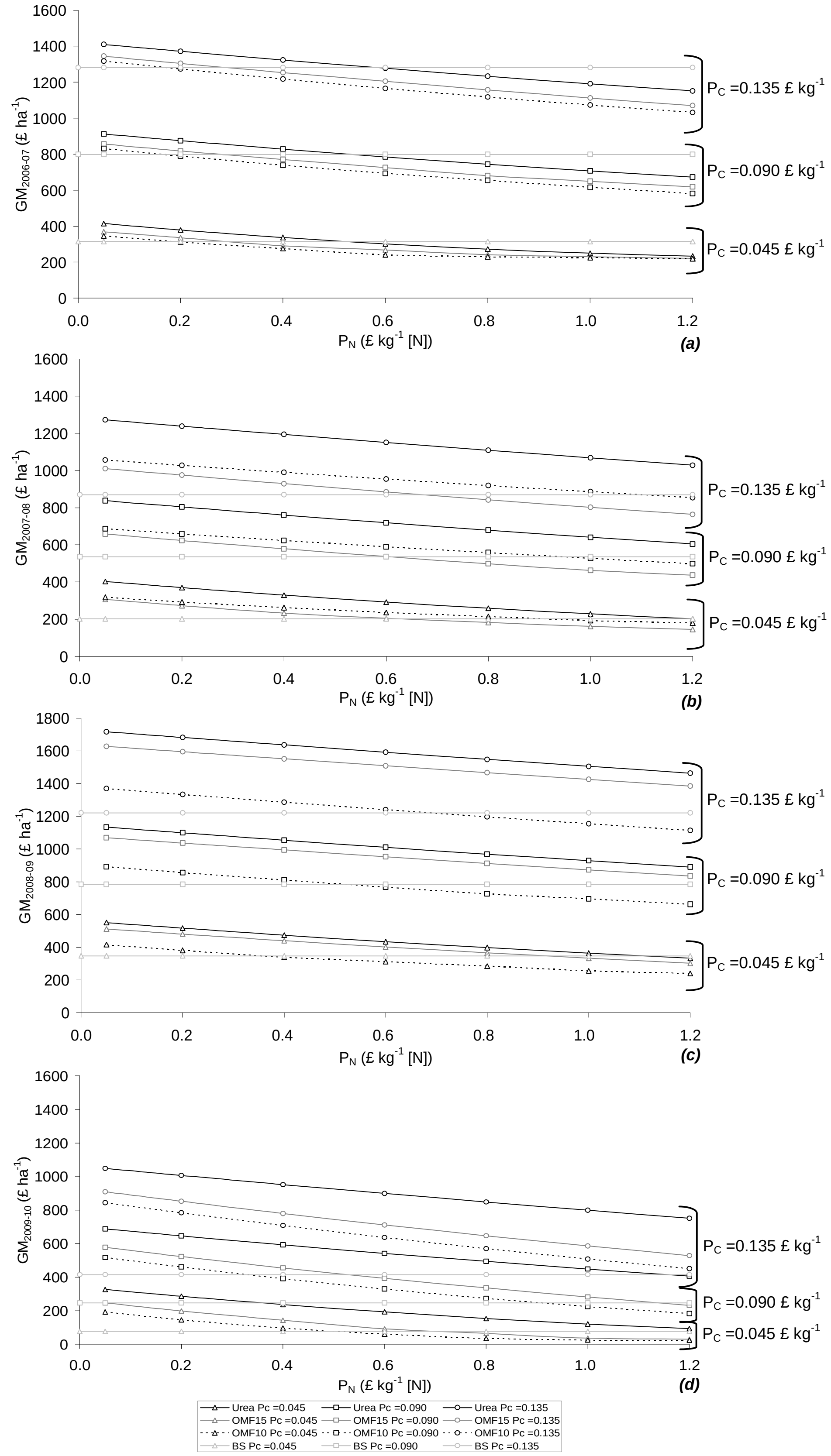


Figure 8.5: Sensitivity analyses for Avenue Field (*a*: 2006-07; *b*: 2007-08) and Chippies Field (*c*: 2008-09; *d*: 2009-10). Fertiliser application charged at contractor's price.

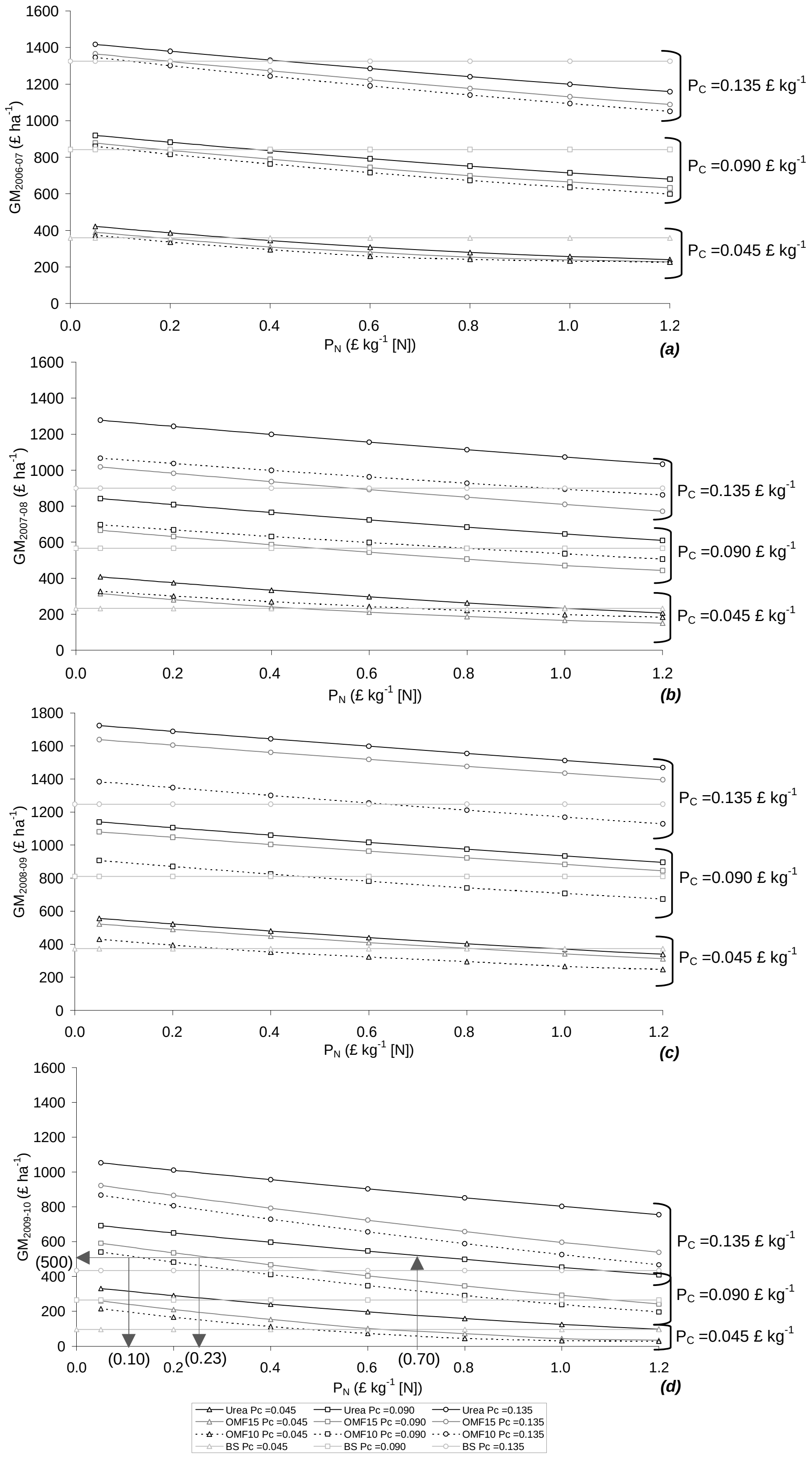


Figure 8.6: Sensitivity analyses for Avenue Field (*a*, 2006-07; *b*, 2007-08) and Chippies Field (*c*: 2008-09; *d*: 2009-10). Fertiliser application charged at farmer's average cost [Data for 2015 in brackets].

This approach to pricing implies that the $P_{N\text{-}OMF}$ should behave as a ‘follower’ of the $P_{N\text{-}Urea}$ so that gross margins are not affected. A disadvantage is that it does not address the issues associated with the increase in the total nitrogen load of the farm which can arise as a result of higher MERN, and thereby imposing a potential restriction to the use of OMF if working within NVZ.

An alternative is that OMF-N was priced at the equivalent price of urea-N and that farmers were compensated for the loss of income. If OMF-N was to be applied at a rate equivalent to the MERN of urea for each of the four years’ trial, the expected grain yield for OMF_{10} and OMF_{15} can be inferred from the response curves. This would produce a mean nitrogen application rate of 225 kg [N] ha^{-1} which corresponds to the mean MERN encountered for urea in the four years’ trial (**Table 8.2**). Solving the response functions for this level of nitrogen fertilisation, it results that the mean grain yields for OMF_{10} and OMF_{15} over the four years’ trials are 8825 and 9301 kg [grain] ha^{-1} respectively. Therefore, the differential yields with urea (10347 kg [grain] ha^{-1}) are, respectively, 1522 and 1046 kg [grain] ha^{-1} for OMF_{10} and OMF_{15}. These represent gross incomes of £136.98 and £94.14 per hectare respectively at P_C =0.090 £ kg^{-1} [grain]. These differences in grain yield with respect to urea reflect the differences in the efficiency of the nitrogen applied for the same level of nitrogen fertilisation.

The differential cost of spreading, that is the difference between the spreading cost of urea and OMF, should be added to the differential gross incomes so that the perceived gross margins remain the same to that obtained from the use of urea (**Table 8.5**). Therefore, the spreading costs of the required nitrogen rate of 225 kg [N] ha^{-1} at the mean contract charge and the mean farmer’s cost of broadcast spreading have been estimated at 48.90 and 35.55 £ ha^{-1} for OMF_{10}, and 37.84 and 27.50 £ ha^{-1} for OMF_{15} respectively. The cost of spreading of urea at the same nitrogen rate was on average for the four years’ trials 20.18 £ ha^{-1} (mean contractor’s charge) and 14.66 £ ha^{-1} (mean farmer’s cost). These costs are shown in **Table 8.7**.

Table 8.7: Differential gross income (£ ha^{-1}) between urea and OMF_{10} and OMF_{15}. The price of the crop is taken at the constant price (1994-2010) of 0.090 £ kg^{-1} [grain].

Fertiliser/	**OMF_{10}**		**OMF_{15}**		
Spreading option	**Cont’r**	**Farmer**	**Cont’r**	**Farmer**	**Unit**
[1]**ΔY ($Y_{Urea} – Y_{OMF}$)**	1522	1522	1046	1046	[kg ha^{-1}]
[2]**ΔGI ($GI_{Urea} – GI_{OMF}$)**	136.98	136.98	94.14	94.14	[£ ha^{-1}]
[3]**ΔCost of spreading ($C_{Urea} – C_{OMF}$)**	28.72	20.89	17.66	12.84	[£ ha^{-1}]
[4]**Total [2 + 3]**	**165.70**	**157.87**	**111.80**	**106.98**	**[£ ha^{-1}]**

The income generated by United Utilities plc from selling OMF, assuming P_N =0.65 £ kg^{-1} [N] which was the mean price of urea-N for the period 2007-10 (Nix, 2007-10), would be **146.25 £ ha^{-1}**; **i.e. 225 kg [N] ha^{-1} x 0.65 £ kg^{-1} [N]**. Therefore, if the company was to compensate farmers for the loss of income at the figures estimated in the table above, for every 225 kg [N] the company sells in the form of OMF-N, it would make a loss of **£19.45** or **£11.62** with **$\mathbf{OMF_{10}}$** depending on the selected spreading alternative whereas it would make revenues of **£34.45** or **£39.27** with OMF_{15} also depending upon the spreading choice. If the company was responsible for the field application of OMF and the cost of spreading being met by the company, then the compensation to farmers should only be done for the sum equivalent to the differential gross incomes with respect to urea. These appear to be significantly lower than the gross income from selling OMF-N. Some of the costs (fixed) associated with spreading may be diluted if the number of hectares per year is increased.

A cost model for the production of OMF prepared by the United Utilities plc (Gedara and Le, 2008) suggested that producing OMF_{15} and OMF_{10} would cost 267 and 235 £ t^{-1} of sludge (dry solids basis) respectively. The difference in the cost of production between the two materials is mainly due to the higher cost of nitrogen added to the OMF_{15} in the form of urea. However, since 1 tonne of sludge (dry solids basis) yields approximately 1.64 tonnes of OMF_{15} and 1.4 tonnes of OMF_{10}, it results that the costs of production expressed in £ t^{-1} [OMF] are 162.80 £ t^{-1} [OMF_{15}] and 167.85 £ t^{-1} [OMF_{10}] respectively. If farmers were to be compensated for the loss of income as a result of the use of OMF instead of urea, then it is helpful to express the cost of production of OMF in £ ha^{-1}. The figures given above in £ t^{-1} [OMF] translated into £ ha^{-1} assuming a nitrogen application rate of 225 kg ha^{-1} and excluding the cost of spreading are 244.20 and 377.75 £ ha^{-1} for OMF_{15} and OMF_{10} respectively which added to the differential gross incomes shown in **Table 8.7** result in 338.34 and 514.73 £ ha^{-1} for OMF_{15} and OMF_{10} respectively. By deducting the income generated from selling OMF-N, which was estimated at 146.25 £ ha^{-1}, it results that farmers should be compensated by 192.09 and 368.48 £ ha^{-1} if they were to apply OMF_{15} or OMF_{10} respectively at the rate corresponding to the MERN of urea-N.

At United Utilities plc, the cost of recycling of biosolids to agricultural land (Gedara and Le, 2008) was estimated at 80 £ t^{-1} of sludge (dry solids basis). Assuming that the application rate of biosolids-N was 246 kg [N] ha^{-1} which is equivalent to the N_{max} obtained on average for the four years' trial (**Table 8.2**), and that their mean nitrogen concentration is [$\overline{N}$] =4.47%; to be able to meet the crop's nitrogen requirement, biosolids should be applied at a rate of *c*.5.5 t ha^{-1}. Hence, the cost of recycling can be estimated at *c*.440 £ ha^{-1}.

This figure (440 £ ha^{-1}) includes the spreading cost of biosolids for which it is fairer to add the cost of spreading OMF; i.e. the differential cost with respect to urea, to the amounts by which farmers should be compensated for the use of OMF. These equate to the total values given in **Table 8.7**. It is important to highlight that the price of OMF-N used for this analysis is equivalent to the price of urea-N, i.e. 0.65 £ kg^{-1} [N]. A summary of the proposed approach is shown in **Table 8.8**.

Table 8.8: Financial compensation (£ ha^{-1}) to farmers for the use of OMF instead of urea as a source of nitrogen.

Fertiliser/	**OMF$_{10}$**		**OMF$_{15}$**		
Spreading option	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**	**Unit**
[1]Cost of OMF production	377.75	377.75	244.20	244.20	[£ ha^{-1}]
[2]ΔGI (GI$_{Urea}$ – GI$_{OMF}$)	136.98	136.98	94.14	94.14	[£ ha^{-1}]
[3]ΔCost of spreading (C$_{Urea}$ – C$_{OMF}$)	28.72	20.89	17.66	12.84	[£ ha^{-1}]
[4]Subtotal [1+2+3]	543.45	535.55	356.00	351.18	[£ ha^{-1}]
[5]Income from selling OMF	146.25	146.25	146.25	146.25	[£ ha^{-1}]
[6]Total [4–5]	**397.20**	**389.30**	**209.75**	**204.93**	**[£ ha^{-1}]**

It can be seen from the table that the total costs to the company, if it decided to compensate farmers for the loss of income as a result of the use of OMF instead of urea, appear to be significantly lower than the cost of recycling biosolids when these are expressed per unit hectare (estimated at 440 £ ha^{-1}). Hence, **savings of *c*.46.75 £ ha^{-1} (range 42.80-50.70 £ ha^{-1}) for OMF$_{10}$ or *c*.232.66 £ ha^{-1} (range 230.25-235.07 £ ha^{-1}) for OMF$_{15}$** can potentially be made by recycling biosolids in the form of OMF instead of biosolids as such.

However, it is important to note that for every hectare, the company can dispose a total of 5.5 tonnes [dry solids] of biosolids whereas it is reduced to 1.62 or 0.92 tonnes of biosolids per hectare if the disposal is done through OMF$_{10}$ or OMF$_{15}$ respectively. This is implying that biosolids-N is applied at a rate of 246 kg [N] ha^{-1} (for [$\overline{N}$] =4.47%) and OMF-N is applied at 225 kg [N] ha^{-1} (assuming the formulations carry 10% and 15% N respectively). Therefore, if the same biosolids' disposal target (tonnes [biosolids] y^{-1}, dry solids basis) was to be met, the land-bank for recycling would need to be increased by approximately the following ratios:

$$1.0 \text{ ha (biosolids)} \approx 3.5 \text{ ha (OMF}_{10}) \approx 6.0 \text{ ha (OMF}_{15})$$

The challenge appears to be in developing the market and avoid compromising the total (current) amount of biosolids disposed through agriculture. Expanding the land-bank for recycling can result in increased costs of transport which were not included in this simple analysis.

The sensitivity analyses undertaken (**Figures 8.5-8.6**) also provided an indication of the level of financial compensation needed if changes in the price of the grain or urea-N occur. The pricing strategies discussed; i.e. the **first** where the price OMF-N behaves as a 'follower' of the price of urea-N, and the **second** where it exactly matches the price of urea-N, do not take account of some issues regarding the perceived market value of OMF. In an attempt to determining the price of OMF but taking into account the customer's perception of the products a simple choice experiment was conducted. In addition, a methodological approach for the investigation of the farmers' willingness to pay for OMF using contingent valuation is presented and discussed. The following sections introduce and discuss the various techniques available to determine the perceived market value of goods and services (**Section 8.5**), the results of a pilot choice experiment (**Section 8.6**) and the contingent valuation method (**Section 8.7**).

8.5 Perceived market value of OMF

Stated preference techniques (SP) have been widely used to obtain economic valuations of goods or services. They refer to questionnaire-based methods which aim at revealing individuals' preferences (Bateman et al., 2002). They try to elicit individuals' monetary valuations of costs and benefits, and these valuations are generally referred to as willingness to pay (Bateman et al., 2002). Therefore, a relatively simple way of investigating the willingness to pay (WTP) is by asking consumers what they would be prepared to pay for goods or services or whether they are willing to pay a determined amount. In some cases, respondents are asked to show their preferences when presented with a number of different choices (Bateman et al., 2002). These types of techniques are often applied when information regarding WTP for particular goods or services cannot be directly inferred from the market (Bateman et al., 2002).

As highlighted in **Section 8.1**, OMF is not only a new product to United Utilities plc but also to the fertiliser market for which an acceptable market price for the product ought to be determined. The two most common stated preference approaches are choice modelling and contingent valuation. Choice modelling comprises a number of different techniques; namely, choice experiments, contingent ranking, contingent rating, and paired comparisons (Pearce et al., 2006).

These techniques differ in the quality of the data they can provide, the accuracy of the WTP estimates and their consistency with typical measures of welfare change (Pearce et al., 2006).

In order to investigate the farmers' acceptance of OMF, a pilot choice experiment was initially conducted. In addition, it was considered that the technique would be appropriate to derive WTP estimates of OMF. The results of this pilot exercise, along with the difficulties encountered in applying the technique, are discussed in **Section 8.6**. The other three choice modelling techniques indicated above were discarded since they were considered to be not applicable to the purpose of this research. As highlighted by Pearce et al. (2006), they require respondents to rank options (contingent ranking) or to score a set of scenarios given either individually (contingent rating) or in pairs (paired comparisons).

An alternative approach to deriving WTP estimates of goods or services is by means of a method known as contingent valuation. This method is also grouped as part of stated preference techniques and it uses surveys as instruments to gather information on people's WTP for goods or services (Pearce et al., 2006). A review of this technique and its possible application for the investigation of farmers' WTP for OMF is presented and discussed in **Section 8.7**. It draws upon the methodology used by Pegurara-Gasparin (2009) who satisfactorily applied the technique to investigate the acceptance of and the willingness to pay for on-farm automated traceability systems reported in earlier studies (Peets et al., 2008; Peets, 2009). Time did not permit the collection of experimental data; however, the method is presented as a comprehensive tool to investigate the farmer's WTP for OMF and it is understood that it will provide a platform for future research into the subject. The pilot choice experiment and the contingent valuation methodology are presented as tools to investigate both the acceptance of OMF and the farmers' WTP for OMF respectively.

8.6 Choice experiment

8.6.1 Introduction

A pilot investigation was conducted using a method known as choice experiment. The choice experiment methodology was originally applied by Louviere and Hensher (1982) and also Louviere and Woodworth (1983). It is supported by the random utility theory (Luce, 1959; McFadden, 1973) which suggests that individuals, acting rationally, will choose in order to maximise their utility (Bateman et al., 2002; Pegurara-Gasparin, 2009).

Bateman et al. (2002) also stated that the choice experiment methodology is compatible with both the utility maximisation and demand theories when a status quo choice is given in the set of alternatives. The technique has also been employed as a non-market valuation tool (e.g. McFadden, 1986; Lusk and Hudson, 2004; Hensher et al., 2005; Travisi et al., 2006; Travisi and Nijkamp, 2008) to identify the criteria that most influence people's decision when acquiring a particular product or service. It is used to determine the characteristics or attributes of a product that consumers prefer most and therefore are willing to pay for. When the price or the cost of the product is considered as one of the attributes of the goods or services, WTP may be inferred from the respondents' choices (Pearce et al., 2006). In the current study, the choice experiment methodology was used to try and identify the fertilisers' attribute/s that farmers would consider to be important, and consequently, would be willing to pay for.

8.6.2 Methodology

The choice experiment methodology consists of selecting one or more alternatives where one of them is the status quo or baseline alternative (Pearce et al., 2006). It requires dividing the attributes into different levels and providing values indicators for each of the levels previously defined (Pegurara-Gasparin, 2009). In order to comply with this requirement, a simple questionnaire was first drawn and it is shown in **Appendix A.8.2**. The questionnaire was designed to have 2 levels; i.e. two fertiliser products (Product A, a standard fertiliser already in the market – urea – and Product B – OMF_{15}), and 3 attributes which were the nitrogen and phosphorus contents, and the fertiliser price. The phosphorus content of the standard fertiliser (urea) is zero. One of the levels – the status quo (Product A) – and its attributes were held constant for all the combinations with the second level (Product B). Comparisons between the products were made for different combinations of the chosen attributes and included either an improvement and/or a worsening of the situation. For example, high N and P contents and high price or high N and P content and lower price.

The pilot questionnaire was emailed out to twelve respondents from Cranfield University who were believed to have some awareness of fertilisers and fertiliser practices. They were asked to answer the questionnaire and to choose one of the two products for each one of the combination of attributes. As highlighted earlier, the analysis of the data coming from the experiment uses the random utility theory which is based on the assumption that respondents would proceed rationally by choosing the alternative that results in the highest utility (Bateman et al., 2002).

Hence, the probability of selecting a particular alternative will be increased when the utility provided by such choice is the highest amongst the available choices (Loureiro and Umberger, 2007; Pegurara-Gasparin, 2009). The price of N-fertiliser used for the exercise was that reported by Nix (2009) and corresponded to the mean nitrogen price of urea-N ($P_{N\text{-}Urea}$ =1.04 £ kg^{-1}) for 2008. A statistical analysis was undertaken (**Appendix A.8.4**) using NLOGIT 4.0.1 (Greene, 2007) to aid identifying whether there were significant correlations between the chosen attributes.

8.6.3 Results and discussion

A total of ten (out of twelve) respondents returned their questionnaires together with a brief description of their views of the questionnaire as reported in **Appendix A.8.3**. The statistical analysis indicated that there was a positive correlation (R^2 =0.94; p=0.0005) between the nitrogen content in the fertiliser and the fertiliser price. In addition, it was indicated that the phosphorus content in the fertiliser was negatively correlated (R^2 =-0.21; p=0.43) with the price of the fertiliser. This suggested that farmers would be willing to pay a higher price for a product that contains a lower phosphorus concentration and higher nitrogen content or even a higher price for a product that contained only nitrogen. It appeared that nitrogen was the major determinant of the fertiliser price.

This is not totally true as a fair price for phosphorus would still be paid if the nutrient was needed; e.g. a situation where soil-P index was below the target level or where phosphorus was required as part of the fertilisation plan to maintain the fertility status of the soil. Given the responses obtained, the questionnaire was re-designed to include a fourth attribute; namely, potassium content. Comparisons were subsequently made against a standard compound NPK fertiliser (20:10:10) instead of urea implying that all three nutrients in the fertiliser were needed. The price of NPK fertiliser used for this exercise was £220 per tonne [product] as reported by Nix (2009). Following the inclusion of a fourth attribute, the resultant combination of both attributes and levels produced a questionnaire which had a total of 16 questions and it became far too complex to solve by the respondents (**Appendix A.8.5**). The complexity of the questionnaire was reflected in the poor number of responses being returned. In fact, these were not sufficient to undertake a statistical analysis for which the work could not progress. Therefore, a recommendation may be made to further investigate what criteria influence farmers' decisions when purchasing compound fertilisers; e.g. reliability, nutrient concentration, cost of application, intended end use, handling and storage, and to target the survey mainly to NPK fertiliser type users.

It can be stated that farmers that typically use straight nitrogen sources would not be immediately interested in compound fertilisers unless the price of the fertiliser, and in particular, the price of nitrogen, or other attribute becomes clearly advantageous. In order to produce a simple questionnaire which is easy to answer, the inclusion of more than three attributes may be avoided. For this, it is important to be able to identify the most relevant attributes of the product and inform the respondent on some of the potential benefits associated with its use. In this respect, the inclusion of some basic technical information about the product, in addition to the nutrients' concentration, such as its agronomic performance, may be of help in assisting respondents answering the questionnaire while it would provide a more reliable output. A preliminary step could be enquiring farmers about the characteristics sought in a typical NPK fertiliser so that a more robust survey can be constructed thereby leading to better results.

8.6.4 Conclusions choice experiment

- The questionnaire should be simple, easy to answer and understand by the respondent who should also have some basic knowledge of the product and be ideally familiar with the use of compound NPK fertilisers. Technical information of the product should also be given to aid responding the questionnaire accurately and provide a more reliable output.
- The relatively low nutrients' concentration of OMF should be reflected in the price of the product. To certain extent, this can help to offset the expected increase in the cost of application so that their associated costs are of similar order of magnitude to those of the fertiliser products already in the market. It is important to investigate what attributes of NPK fertiliser the farmers are interested in and what factors affect the decision making process and the choice of a particular fertiliser product. Subsequently, the experiment should be repeated to compare OMF with a compound NPK fertiliser instead of a straight N-fertiliser.
- The results of this simple pilot choice experiment, however, appeared to indicate that the nitrogen content in the fertiliser is the main factor influencing fertiliser choice.

8.7 Contingent valuation

8.7.1 Introduction

As highlighted in **Section 8.5**, contingent valuation (CV) is a stated preference (SP) technique which can be used to estimate the WTP for non-market goods. The use of contingent valuation requires drawing a questionnaire which sets out a hypothetical market where the goods can be traded (Mitchell and Carson, 1989). A sample of people, randomly selected, is directly asked to express their WTP for a hypothetical change in the level of provision of the goods (Pearce et al., 2006). The CV assumes that the people in the sample will behave in the way they would if they were in a real market situation (Pearce et al., 2006). The values obtained may be then treated as approximations of the value of the non-market goods (Pegurara-Gasparin, 2009).

Although CV has often been used to determine the economic value of non-market environmental commodities (Pegurara-Gasparin, 2009), the work of Cameron and James (1987), and later Yoo (2002), have satisfactorily used it as an instrument to pre-test the market of certain goods and services, and it has been demonstrated that CV is a robust tool to aid the assessment of the market potential in new product development (Pegurara-Gasparin, 2009). In line with the work of Cameron and James (1987) and Yoo (2002), Pegurara-Gasparin (2009) has satisfactorily applied it to estimate the WTP for automated agrochemical traceability systems. Based upon this later work, an approach to determining the farmers' WTP for OMF using CV is presented.

The aim of this section is to provide a brief overview of the elicitation methods available and to make a recommendation of the most appropriate method for the investigation of the farmers' WTP for OMF. In addition, it aims to provide a guideline for the design of the questionnaire including a set of bids amounts, and to review the procedure for the estimation of the mean, the median, and the maximum WTP from which the demand curve and the breakeven analyses are derived. This procedure is also based on the work of Bateman et al. (2002) and Pegurara-Gasparin (2009). It is understood that this part of the work will provide the basis for future research into the subject and it will contribute, in addition to the gross margin analysis reported earlier (**Section 8.3**), to the design of the OMF's pricing strategy. Pegurara-Gasparin (2009), after the work of Bateman et al. (2002), indicated the various stages that need to be followed when using CV. These include the following:

- Defining the product and the hypothetical market for the product,
- Selecting the elicitation method and defining the questionnaire in relation to it,
- Defining the size of the sample,
- Pilot-testing the questionnaire, and
- Estimating mean, median and maximum WTP.

The first stage is already known and includes the two OMF products' formulations which are intended for their use in cereal crops and grass; hence, the potential market for the products will be the farming sector associated with cereal crops (mainly wheat) and grass production. In defining the size of the sample when this is relatively large, the survey can be inefficient in terms of the time, money and resources required while very small samples may lead to inaccurate estimates (Amaya-Amaya et al., 2008). In general, choice experiments need a minimum of 30 individuals; however, the larger the accuracy required, the larger the size of the sample (Amaya-Amaya et al., 2008).

8.7.2 The elicitation method

There are a number of elicitation methods available which can be used to ask people about their WTP. According to the work of Bateman et al. (2002) and Pegurara-Gasparin (2009), these are listed below:

- Payment cards,
- Open-ended questionnaires,
- Single-bounded dichotomous choice, and
- Double-bounded dichotomous choice.

These methods have been applied and their advantages and disadvantages reviewed in a number of works (e.g. Mitchell and Carson, 1989; Reaves et al., 1999; Bateman et al., 2002; Whynes et al., 2003; Pearce et al., 2006 among others). The work undertaken by Pegurara-Gasparin (2009) employed the double-bounded dichotomous choice method whereby a single dichotomous type of question such as "Are you willing to pay £*x*?" is followed by a second question of the same nature. When the response to the first question was affirmative, then the bid was increased in the second question or it was decreased if the answer was negative. The double-bounded dichotomous choice is said to be less affected by biases such as starting point and strategic type of biases, and does not have the same requirements in terms of sample size compared with the other methods listed above (McLeod and Bergland, 1999; Hanemann and Kanninen, 1996; Pearce et al., 2006; Pegurara-Gasparin, 2009).

With regards to the survey method, there are also a number of alternatives which include the following, as listed by Pegurara-Gasparin (2009):

- Face-to-face interviews (e.g. Arrow et al., 1993),
- Mail surveys (e.g. Mannestro and Loomis, 1991),
- Online web-surveys (e.g. Tsuge and Washida, 2003; Pegurara-Gasparin, 2009).

The expected rate of response despite being generally low (*c*.10%) in web-based questionnaires (Marta-Pedroso et al., 2007), it is inexpensive (Pegurara-Gasparin, 2009) and a fair amount of responses can be obtained if targeted at a large sample. This methodology may be recommended to United Utilities plc which has direct access to a large number of customers involved in the practice of recycling biosolids and who are aware of the company's new product developments. The questionnaire can be up-loaded on to the company's OMF's website (http://enzymichydrolysis.com/) for public access. Pegurara-Gasparin (2009) suggested offering a prize as an incentive to encourage people to answer the questionnaire thereby increasing the rate of response.

8.7.3 Design of the questionnaire

The design of the questionnaire is a key aspect of the study; its aim is to elicit individuals' preferences, expressed in monetary terms, for variations in the quantity and/or quality of goods or services as stated by Pearce et al. (2006). Following the guidelines set out by Pearce et al. (2006), a questionnaire should be designed to comprise three parts:

- **Part 1:** includes a set of attitudinal and behavioural questions about the goods which aim at uncovering the factors driving people's attitude towards the goods,
- **Part 2:** includes the contingent scenario and respondents are interrogated to find out how much the goods are valued under a set of specified circumstances, and
- **Part 3:** includes a set of questions targeted at obtaining information on the socio-economic characteristics of the respondent to provide a better understanding of the background factors influencing responses, assess the representativeness of the sample and investigate how WTP varies with respect to individuals' characteristics.

Subsequently, econometric techniques can be applied to the results of the survey allowing the mean and the median WTP to be derived (Pearce et al., 2006).

Following the guidelines outlined above and based on the work of Pegurara-Gasparin (2009), the questionnaire for this present study can be subdivided into 3 parts containing a mixture of multiple choice and open-ended questions.

The **first** part of the questionnaire should aim at investigating the characteristics of the farm, the details of the spreading equipment and fertilisation practices, including the fertiliser types and application rates used on the farm in relation to the soil types and the crops encountered on the site. The **second** part should inform on the OMF concept and it should contain the double dichotomous choice questions. An open-ended question of the sort "What is the maximum amount you would pay for OMF?" should also be included. Finally, the **third** part should gather socio-economic information of respondents. The questionnaire for this study can be drawn to divert respondents to four different paths according to the type of farming and the spreading practice, as follow:

- **Group 1:** Farmers who grow mostly arable crops and perform the spreading of fertiliser employing contractors,
- **Group 2:** Farmers who grow mostly arable crops and perform the spreading of fertilisers with their own equipment and labour,
- **Group 3:** Farmers who grow mostly grass and perform the spreading of fertiliser employing contractors, and
- **Group 4:** Farmers who grow mostly grass and perform the spreading of fertiliser with their own equipment and labour.

As highlighted in **Chapter 3**, both OMF formulations can potentially be applied on arable crops and grass. It is therefore important to identify which of the two OMF formulations is more suited (or preferred) to the type of farming activity and consequently farmers are willing to pay a fairer price in each situation. This would aid the marketing strategy by targeting a particular formulation to a specific crop or soil type supported also by technical evidence from the field studies at conducted Silsoe Farm. In addition, it is important to identify whether contracting or doing spreading operations with the farmers' own equipment and labour can significantly affect the WTP for the products. Another possibility is to group up the farmers according to the size of their farms, regardless of the crops grown on the farm. For example, the questionnaire can divert the respondents to three different groups of farms – small (<250 ha), medium (up to 750 ha), and large (>750 ha). As highlighted earlier, the questionnaire needs to be pilot-tested before being sent out so as to allow for corrections and adjustments (Bateman et al., 2002).

8.7.4 Bids amounts

The double bounded dichotomous choice type of question is presented in a sequence having two bids to which the respondent is asked for a *yes* or *no* answer. The answer to the second question is subjected to the response to the first bid so that the bid offer in the subsequent question is lower when the answer was *no* or higher if the answer was *yes* (Pegurara-Gasparin, 2009). The recommended set of bids based on the price of nitrogen is presented in **Table 8.9**. The initial bid (**B_i**) presented is then followed by a lower bid (**B_{Li}**) if the first bid was rejected or by a higher bid (**B_{Hi}**) if the first one was accepted. The proposed sets of bids should be randomly distributed among the four groups of farmers suggested in **Section 8.7.3**. It is important to note that each respondent will receive only one set of bids so that each respondent replies to one bids' level only.

Table 8.9: Recommended bids for OMF based on the price of nitrogen (£ kg^{-1} [N]).

B_i	**B_{Li}**	**B_{Hi}**	**Unit**
0.10	0.05	0.15	£ kg^{-1} [N]
0.30	0.25	0.35	£ kg^{-1} [N]
0.50	0.45	0.55	£ kg^{-1} [N]
0.70	0.65	0.75	£ kg^{-1} [N]
0.90	0.85	0.95	£ kg^{-1} [N]

Pegurara-Gasparin (2009) recommended the lower (B_{Li}) and the higher (B_{Hi}) bids to be in the range ±10% of the middle value of the initial bids' range in order to avoid overlapping between the different bids' levels. As can be read off the tables above, the middle value based on the price of nitrogen is B_i =0.50 £ kg^{-1}; hence, B_{Li} and B_{Hi} are ± £0.05 of B_i. When the price of NPK is taken as a reference B_i =300 £ t^{-1}; hence, B_{Li} and B_{Hi} are ± £30 of B_i.

The range of initial bids (B_i) was estimated based on the results of the gross margin analysis (**Section 8.3**) and the regression analyses conducted for the nitrogen fertiliser price (**Section 8.2.2**). For the first set of bids, by selecting a minimum initial bid B_i =0.10 £ kg^{-1} [N], the resultant lower and higher bids were consistent with the range of mean prices of OMF-N needed to match ±1% of the crop's gross margin obtained with urea (**Table 8.6**) for which the information obtained from the survey can be applicable to both OMF types depending on the responses obtained. The highest initial bid (B_i =0.90 £ kg^{-1} [N]) was selected based on the results of the regression analysis when the price of urea was projected to 2015 (**Figure 8.2c**).

This value corresponds to the upper limit of the 95% confidence interval fitted to the linear model for 2015 when the full price dataset (1994-2010) was included in the trend. The use of this price level was considered to be a realistic approach which was in line with the relatively high volatility observed in the fertiliser (and energy) prices as discussed earlier (**Section 8.2.2**). Each set of bids was subsequently separated at regular increments of £0.20.

The range of bids selected does not go as high as the peak of nitrogen prices recorded for urea-N in 2008 when the $P_{N\text{-Urea}}$ was 1.04 £ kg^{-1} (Nix, 2009). However, the possibility of a farmer having the willingness to pay for such high amount can still be investigated by means of an open-ended question when respondents are asked to state "What is the maximum price you would pay for OMF?" as highlighted earlier (**Section 8.7.3**). From the marketing perspective, knowledge of the WTP for OMF for each group of farmers is also important so that more effort can be spent on promoting the product on the segment that shows the highest WTP which can, therefore, result in higher revenue.

Alternatively, the set of bids can also be designed on the basis of the price of a compound NPK fertiliser (20:10:10). The bids amounts shown in **Table 8.10** use current (2010) and expected fertiliser prices (**Figure 8.3**).

Table 8.10: Recommended bids for OMF based on the price of NPK fertiliser (£ t^{-1}).

B_i	B_{Li}	B_{Hi}	Unit
50	25	75	£ t^{-1} [NPK]
150	125	175	£ t^{-1} [NPK]
250	225	275	£ t^{-1} [NPK]
350	325	375	£ t^{-1} [NPK]
450	425	475	£ t^{-1} [NPK]

As can be seen from the table, the middle value (B_i =250 £ t^{-1}) is similar to the mean price of 20:10:10 recorded for 2010; i.e. 255 £ t^{-1}. The highest initial bid (B_i =450 £ t^{-1}) is similar to the peak price recorded in 2008; i.e. 457 £ t^{-1}. The regression analysis (**Figure 8.3**) indicated that the expected price of NPK in 2015 would be 295 £ t^{-1} (range 185-395 £ t^{-1} for the ±95% confidence interval) which also falls in the range of bids proposed above. A recent quotation provided by Southern Water for Bestway® fertiliser (Spence, 2010) suggested a price of 26 £ t^{-1}. Therefore, the use of B_i =50 £ t^{-1} as the lowest initial bid allows its lower boundary to be consistent with the market price of a similar product.

8.7.5 Mean and median willingness to pay

One of the objectives of the WTP analysis is to be able to determine a measure of the *average WTP* of individuals in the sample whose aggregation should be a representative indication of the WTP of the whole population (Bateman et al., 2002; Pearce et al, 2006). The approach proposed by Bateman et al. (2002) applies a non-parametric estimation of the mean and median WTP which allows calculating both measures without making distributional assumptions; e.g. normal, logistic, log-normal distributions. This is important since the mean could be very sensitive to the type of distributional assumption made. The non-parametric method is an empirical approach to approximating the survivor function of WTP responses.

The survivor function basically indicates the probability of observing a higher WTP than a particular value (Bateman et al., 2002). The estimation of the survivor function is done by applying the Kaplan-Meier estimator and the mathematical procedure is explained in full in Bateman et al. (2002). When analysing continuous data, WTP values are put into ascending order so that the survivor function is obtained by calculating the proportion of the sample that has a WTP greater than each value. However, when using double-bounded dichotomous choice questions, the two answers provided by the respondents will show one of the following scenarios into which their WTP will fall (from Bateman et al., 2002):

- “No” to B_i followed by “No” to B_{Li} $\therefore$ WTP is between 0 and B_{Li},
- “No” to B_i followed by “Yes” to B_{Li} $\therefore$ WTP is between B_{Li} and B_i,
- “Yes” to B_i followed by “No” to B_{Hi} $\therefore$ WTP is between B_i and B_{Hi}, and
- “Yes” to B_i followed by “Yes” to B_{Hi} $\therefore$ WTP is between B_{Hi} and ∞.

It can be seen that although the bids’ levels shown in **Table 8.9** do not overlap, the possible answers given by respondents will produce overlapping intervals. For example, an individual answering “No”, “No” in the second bid level given in the table (B_i =0.30) will have a WTP which will fall in the interval 0-0.25. This interval will overlap with respondents answering “No”, “No” or “No”, “Yes” in the first bid level (B_i =0.10) which will produce WTP estimates falling in the intervals 0-0.05 and 0.05-0.10 respectively. This overlapping requires the treatment of the data with a technique known as Turnbull’s self-consistency algorithm (TSCA). A detailed mathematical explanation of the technique can also be found in Bateman et al. (2002) [refer also to Pegurara-Gasparin (2009) to explore into the practical application of the technique].

The responses to the double-bounded dichotomous questions can be categorised according to the interval. The proposed design, as shown earlier in **Table 8.9**, specifies a total of 20 different WTP intervals; i.e. there are four possible intervals for each one of the bids levels defined such that each interval is defined between 0-B_i, B_i-B_{Li}, B_{Li}-B_{Hi}, and B_{Hi}-∞ respectively. This arrangement results in 17 distinct boundary values for the various intervals as indicated below:

0, 0.05, 0.10, 0.15, 0.25, 0.30, 0.35, 0.45, 0.50, 0.55, 0.65, 0.70, 0.75, 0.85, 0.90, 0.95, and ∞.

These boundary values, (B_j), where B_0 is zero and B_{j+1} is ∞, allow defining 16 intervals called *basic intervals* which do not overlap such that interval *j* indicates the basic interval between the boundary values B_{j-1} and B_j (Bateman et al., 2002). The TSCA technique investigates the survivor function at each of the boundary values B_j. The method assumes that the survivor function at 0; i.e. S (B_0), equates to 1 (all respondents will accept the product at price zero) and that at ∞; i.e. S (B_{j+1}), it equates to 0 (it is highly unlikely that a respondent will have an infinite WTP for the product). The steps towards obtaining the mean and the median WTP by means of the Kaplan-Meier and the TSCA techniques are summarised in the following paragraphs. In addition, the non-parametric analysis for the estimation of the mean and the median should include an estimation of the variance of WTP in the population and the 95% confidence intervals of the mean WTP.

The steps towards obtaining the mean and the median WTP have been extracted from Bateman et al. (2002) and the reader may refer to this work if a detailed mathematical explanation of the procedure is required. The **first step** in the application of the TSCA technique is to estimate the number of individuals in the basic interval B_{j-1} to B_j. The results will consist of a series of estimates of the number of respondents lying in each basic, non-overlapping interval. Once this is known, the number of respondents with a WTP greater than the boundary value B_j can be estimated (**second step**).

Subsequently, the Kaplan-Meier estimator can be used to obtain a new set of estimates for the survivor function at these boundary values (**third step**). The procedure is then repeated using the new estimates of the survivor function until the point estimates of the survivor function at each of the B_j converge. The **median WTP** is obtained from this constructed survivor function and it is equivalent to the value at which the survivor function equates to 0.5. The **mean WTP** corresponds to the area under the survivor function. These relationships are shown graphically in **Figure 8.7**.

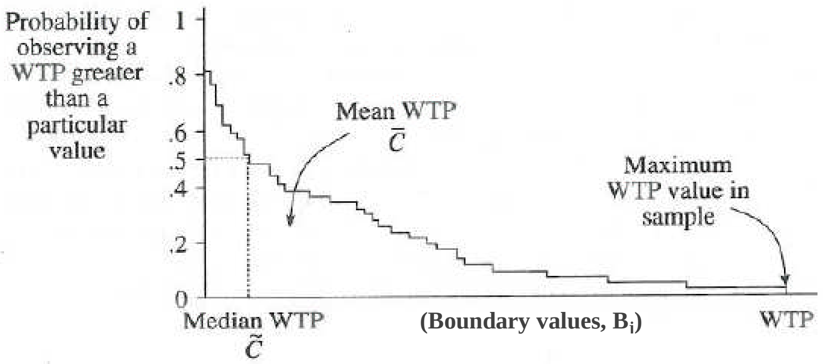


Figure 8.7: Hypothetical Kaplan-Meier survivor function (after: Bateman et al., 2002).

Pearce et al. (2006) highlighted that the mean WTP can lead to overweighting a minority of respondents who have a strong and defined preference but it is, however, the theoretical appropriate measure used in cost-benefit analysis. On the other hand, the median WTP is a superior forecaster of what the majority of customers would indeed be willing to pay. For this reason, both measures need to be estimated.

8.7.6 Maximum willingness to pay

Maximum WTP is determined using the responses to the follow-up question “What is the maximum amount you would pay for OMF?” A graph is then constructed which will show the percentage of the population plotted as a function of its corresponding maximum willingness to pay for OMF. This will allow to know the percentage of people (from the people that perceive a need for OMF) willing to buy OMF at each (maximum) price level. A useful measure is the determination of the mean maximum WTP as well as the standard error and lower and upper 95% confidence intervals. The mean maximum WTP needs to be compared statistically, by means of a t-test, against the mean WTP obtained from the TSCA and Kaplan-Meier analysis to determine if there is a significant difference between the two values. The value showing lower standard error and confidence intervals’ amplitude at 95% is generally preferred with regards to its statistical robustness.

8.7.7 Demand curve and breakeven analysis

The analysis should be completed by constructing a demand curve (**Figure 8.8**) which can also be done based on the results of the follow-up question so that the maximum WTP is plotted against the quantity demanded at each (maximum) price level.

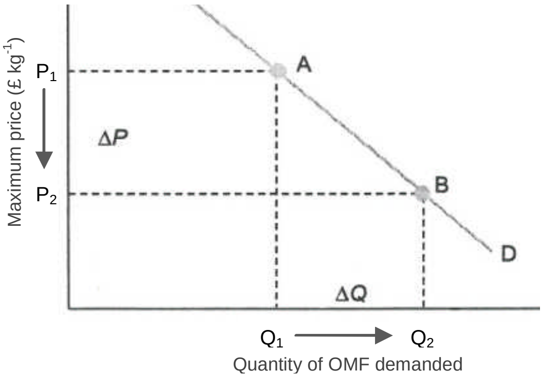


Figure 8.8: Hypothetical demand curve for OMF (adapted from: Rickard, 2006).

The questionnaire should be designed to obtain information about the amount of product likely to be demanded at the maximum price the respondent is willing to pay for OMF. Therefore, the follow-up question may be “What is the maximum price you would pay for OMF and how many tonnes of OMF you would buy at this price?” The quantity of OMF demanded at each (maximum) price level is then estimated by adding-up the quantities required by each respondent at its corresponding maximum price.

The importance of the demand curve is that for any business, knowledge of its level is critical to the generation of revenue which is given by the product of the quantity sold (Q) and the price of the product (P). Hence, an increase in the quantity sold (ΔQ) will increase total revenue. An increase in the price (ΔP) of the product is likely to reduce sales and the issue for the business is how responsive sales are to a change in price (Rickard, 2006). This responsiveness is measured by the price elasticity of demand (ε_P) as shown below (from Rickard, 2006):

$$\varepsilon_P = \frac{\%\ change\ in\ Q}{\%\ change\ in\ P} = \frac{\Delta Q}{\Delta P} \times \frac{P}{Q} \qquad \textbf{[8.13]}$$

Equation [8.13] indicates that given for example $\varepsilon_P = 2$, and whatever the percentage reduction (or increase) in the price, the percentage change in the quantity demanded will increase (or decrease) by twice the percentage. In other words, a 10% reduction in price will lead to a 20% increase in the amount sold.

According to the value of ε_p encountered, this relationship can be categorised as follow (from Rickard, 2006):

- $1 > \varepsilon_p > 0$; demand is price inelastic: an increase (or decrease) in price will increase (or reduce) revenue,
- $\varepsilon_p = 1$; demand is unit elastic: a change in price will lead to an identical percentage change in the quantity demanded therefore revenue will remain constant, and
- $\infty > \varepsilon_p > 1$; demand is price elastic: an increase (or reduction) in price will reduce (or increase) revenue.

Understanding these relationships is important to determine an appropriate pricing strategy for OMF and to maximise revenue. In addition, knowledge of the cost structure for the production of OMF is needed for the breakeven (BE) analysis. BE corresponds to the level of activity (sales) at which there is neither profit nor loss (Atrill and McLaney, 2002). The number of units of output (e.g. tonnes of product) at this point can be estimated with **Equation [8.14]** according to Pegurara-Gasparin (2009):

$$BE_U = \frac{Total\ \ fixed\ \ \cos ts}{Sales\ \ revenue - Variable\ \ \cos ts} \tag{8.14}$$

Where sales revenue is the amount (£) perceived per unit of product (tonne). The BE point (BE_P) is calculated as follow:

$$BE_P = BE_U \times sales\ \ revenue \tag{8.15}$$

Both the breakeven point (£) and unit (tonnes of product sold to BE) need to be compared against the projected quantity demanded from the demand curve to determine whether a profit can be made at each of the price levels investigated.

Strategies to reduce the cost of production may include, for example, an agreement with a major urea producer to buy nitrogen in large quantities and at a lower price than the market and also improved efficiency in the use/recover of energy during the granulation process. It may also be considered the outsourcing of the process and the licensing of the technology to a third party.

It could be an advantage investigating the potential market for OMF at price zero; this information can be derived from the questionnaire and the demand curve. It may be the case that OMF's acceptance is significantly increased if the price of the product is zero. As highlighted in **Section 1.1**, the disposal strategy of United Utilities plc is based on a dual approach to recycling (*c*.70%) and incineration (*c*.30%).

Therefore, there might be a possibility for reducing the cost of disposal if, as a result of increased OMF's acceptance, the amount of biosolids diverted to farmland via OMF is also significantly increased at the expense of incineration which is a more expensive route. This approach is supported by the ultimate objective which is the reduction in the cost of disposal of biosolids, the avoidance of more costly options; i.e. incineration and landfill, and the compliance with environmental regulations.

8.8 Overall discussion

The results of the fertiliser price analysis (**Section 8.2.2**) suggested that, if recent price trends continue, then prices would be 15-20% higher in 2015 compared with 2010's prices. This increase is likely to be observed in both straight nitrogen and compound NPK fertilisers. The results of the linear regression analyses appeared to be in close agreement with projections made by a number of analysts (e.g. Brentnall, 2008; Prince et al., 2009; Heffer and Prud'homme, 2010). The expected increase in fertiliser prices will be driven by a number of factors which includes the increasing cost of energy, the need to meet an increasing demand for food, and also the production of biofuels. In this context, the prospect for the production OMF is encouraging and it is envisaged that there will be a future demand for lower cost fertilisers.

Based on the crop's response curves obtained from the field studies reported in **Chapter 7**, it was possible to provide estimates of the most economic rates of nitrogen application (MERN) and their corresponding grain yields (Y_{MERN}). When the price of OMF-N was assumed to be equivalent to the price of urea-N, the MERN and Y_{MERN} were, on average over the four years' trial, 257 kg [N] ha^{-1} and 9096 kg [grain] ha^{-1} (OMF_{10}), 248 kg [N] ha^{-1} and 9487 kg [grain] ha^{-1} (OMF_{15}), and 225 kg [N] ha^{-1} and 10347 kg [grain] ha^{-1} (urea) respectively. It is expected that improvements in the physical and chemical properties of OMF will significantly improve the agronomic performance of the products and consequently the gross margin of the crops. For the crop amended with biosolids, the MERN and Y_{MERN} were, respectively, 246 kg [N] ha^{-1} and 7908 kg [grain] ha^{-1} which were equivalent to N_{max} and Y_{max} since the price of biosolids-N was considered to be zero.

In addition, the mean spreading cost of biosolids was estimated to be *c*.5.3 times higher than that of urea whereas for OMF_{10} and OMF_{15} it was *c*.3.0 and *c*.2.1 higher than urea respectively. These figures reflect potential savings in both spreading time and spreading costs with the use of OMF compared with biosolids.

The gross margin (GM) analysis, indicated that, when the price of OMF-N was equivalent to the price of urea-N, GM for OMF were in the range of 798.85 to 815.31 £ ha^{-1} (OMF$_{10}$) and 859.37 to 871.05 £ ha^{-1} (OMF$_{15}$). The GM encountered for urea in the same period were 999.89-1005.39 £ ha^{-1} depending, in all cases, whether spreading operations were contracted out or conducted with the farmer's own equipment and labour. The use of biosolids resulted in GM being lower than that of OMF$_{10}$ by *c*.2.9-4.7% and by *c*.10-12.7% compared with OMF$_{15}$ also depending on the costs of spreading. Overall, the lower GM obtained with the use of OMF compared with urea was attributable to the lower level of the response curves of OMF and also to their higher costs of spreading.

It was indicated that in order to be able to match ±1% of GM$_{\text{Urea}}$ with the use of OMF, OMF-N needed to be priced at 0.05 £ kg^{-1} [N] for OMF$_{10}$ and 0.13 £ kg^{-1} [N] for OMF$_{15}$ (on average for the four years' trial). In addition, if the price of OMF-N was to follow the price of urea-N, it should be approximately 0.1*P$_{\text{N-Urea}}$ and 0.2*P$_{\text{N-Urea}}$ for OMF$_{10}$ and OMF$_{15}$ respectively. The reduction in the price of OMF-N needed to match the mean GM of the crop fertilised with urea, resulted, inevitably, in increased MERN values for OMF. These were estimated to be 75 and 55 kg [N] ha^{-1} for OMF$_{10}$ and OMF$_{15}$ above the mean MERN encountered for urea (225 kg [N] ha^{-1}). Therefore, there is a potential restriction to the use of OMF if operating within NVZ which can affect the fertiliser choice.

In order to address this problem, an alternative approach was presented which considered pricing OMF-N at the equivalent price of urea-N and also applying it at the same rate as the MERN needed for urea. Subsequently, financial compensations to farmers would be provided by the company for the potential loss of income. This loss of income can arise from the need to reduce the MERN, on average for the two OMF, by approximately 30 kg [N] ha^{-1} which reduces the expected grain yield (Y$_{\text{MERN}}$) and consequently the gross margin of the crop.

Estimates suggested that in subsidising farmers, the financial compensation needed would be *c*.393.25 £ ha^{-1} (OMF$_{10}$) or *c*.207.35 £ ha^{-1} (OMF$_{15}$). In addition, it was assumed that recycling of biosolids to agriculture costs the company (including spreading) approximately £80 per tonne sludge (dry solids basis). Therefore, if recommendations were made to apply biosolids at the rate equivalent to the MERN (5.5 t [biosolids] ha^{-1}) it would cost the company *c*.440 £ ha^{-1}. Hence, savings of *c*.46.75 £ ha^{-1} (OMF$_{10}$) or 232.66 £ ha^{-1} (OMF$_{15}$) can potentially be made by recycling biosolids in the form of OMF instead of biosolids as such.

In the North West region of England, United Utilities plc produces approximately 215, 000 tonnes per year of sewage sludge (dry solids basis) which are reduced to *c*.150, 000 tonnes (dry solids basis) per year after digestion and *c*.70% of this amount is recycled to farmland; i.e. *c*.105, 000 tonnes per year (dry solids basis). Assuming biosolids were applied at their MERN; i.e. 5.5 t [biosolids] ha^{-1}, the company would need a land-bank of 19, 000 hectares for recycling at a cost of £440 per hectare. This implies that the total cost of recycling biosolids would be approximately £8.4 million per year. On the other hand, the cost of recycling biosolids in the form of OMF, and assuming farmers were subsidised, would be as follow:

- OMF_{10}: 393.25 £ ha^{-1} × 19, 000 ha per year = £7.47 million per year,
- OMF_{15}: 207.35 £ ha^{-1} × 19, 000 ha per year = £3.94 million per year.

Therefore, significant reductions in the cost of recycling could be made compared to biosolids. An important aspect in this analysis is the need to expand the land-bank for recycling in order to meet the same disposal target to that of biosolids; i.e. by approximately 3.5 times for OMF_{10} and by 6 times for OMF_{15}.

Strategies to determine the perceived market value and the farmers' acceptance of OMF products were presented and discussed. The pilot choice experiment conducted indicated that the nitrogen content in the fertiliser was the main factor influencing the fertiliser choice (N.B.: note that these are the results of a small pilot study and not a comprehensive survey involving farmers; therefore, the data obtained should be treated with caution).

In addition, a methodological approach to determining the farmers' willingness to pay for OMF by means of a contingent valuation technique was also presented and discussed. The methodology stated the steps for the design of the questionnaire, the elicitation method, and it recommended the bids amounts (B_i) needed to determine the mean, the median and the maximum WTP for OMF. These were in the range of 0.10 to 0.90 £ kg^{-1} for OMF-N and 50 to 450 £ t^{-1} for OMF as NPK fertiliser. It also outlined the procedure for constructing the demand curve of OMF and conducting the breakeven analysis for OMF production. The contingent valuation technique could be a satisfactory method to determine the farmers' WTP for OMF. The technique provides a robust tool which can be applied for future research into the subject based on the recommended bids amounts.

8.9 Conclusions

The main conclusions coming from **Chapter 8** are summarised below:

- The gross margins analysis indicated that GM were in the range of 798 to 815 £ ha^{-1} (OMF_{10}), 859 to 871 £ ha^{-1} (OMF_{15}) and 999 to 1005 £ ha^{-1} (urea) assuming $P_{OMF\text{-}N} \approx P_{Urea\text{-}N}$.
- In order to be able to match ±1% GM_{Urea} with the use of OMF, the price of OMF-N needs to be reduced to *c*.0.05 £ kg^{-1} (OMF_{10}) or *c*.0.13 £ kg^{-1} (OMF_{15}).
- An alternative approach was proposed which suggested pricing OMF-N at the equivalent price of urea-N and subsidising farmers for the loss of income in comparison with the income perceived with the use of urea. The subsidy needed is approximately 393 £ ha^{-1} when using OMF_{10} or 207 £ ha^{-1} when using OMF_{15}.
- The cost of recycling biosolids was estimated at 440 £ ha^{-1}. Based on the figures indicated above, potential savings of 47 £ ha^{-1} (OMF_{10}) or 233 £ ha^{-1} (OMF_{15}) could therefore be made by subsidising farmers and by recycling biosolids in the form of OMF instead of biosolids as such. This represents a possible reduction in the cost of recycling from £8.4 million per year to £7.47 million per year for OMF_{10} or to £3.94 million per year for OMF_{15}.
- The contingent valuation technique is a reliable method to determine the farmer’s WTP for OMF. It provides a robust tool for future research into the subject based on the recommended bids amounts (B_i in the range 0.10-0.90 £ kg^{-1} for OMF-N or 50-450 £ t^{-1} for OMF as NPK fertiliser). It is imperative to determine what the market needs and to target the product to the segments where it is required. Determining the WTP for OMF would help targeting the product and focusing the marking efforts upon those segments where demand/profitability is likely to be higher.
- The regression analyses conducted indicated that, assuming that recent price trends are maintained, the price of fertilisers in 2015 will be approximately 17-21% greater for straight nitrogen and *c*.15% greater for NPK compared with the prices in 2010.

CHAPTER 9

DISCUSSION

9 DISCUSSION

9.1 Introduction

This chapter discusses the results reported earlier which were obtained both theoretically and experimentally from the studies conducted in the laboratory, the glasshouse and the field. It also refers to some of the elements compiled in the literature review which helped to set out the research context and to support the findings reported. In addition, it highlights those elements that appeared to be missing and upon which a contribution to knowledge is thought to have been made. The aim of the chapter is to integrate the results of this work in a holistic manner to be able to address the overall aim and objectives of this research.

9.2 Recycling of biosolids to farmland – new product development

The production of sewage sludge (biosolids) in England and Wales in 2005 was estimated to be *c*.1.4 million tonnes (dry-solids basis) per annum, and it was indicated that this figure would increase to *c*.1.6 million tonnes (dry soils basis) per year by 2010 (Defra, 2007a). The continuous increase in the production of sewage sludge responds mainly to the growth of the population and the adoption of cleaner technology needed to comply with the standards required for the treatment of effluents, as specified by pertinent regulatory instruments. In this respect, the disposal of sewage sludge is a highly regulated activity (Evans, 1998) and current legislation restricts the opportunities for disposal (Moseley et al., 1998; Moseley, 1999).

Approximately 72% of the total sludge production (*c*.1 million tonnes per year, dry solids basis) is treated to standards suitable for agricultural recycling with the remaining amount being disposed of through incineration and landfill. The recycling of biosolids to farmland is regarded by the UK Government as the best practicable environmental option in most circumstances and it appears to align with the Urban Wastewater Treatment Directive and the general objectives of the waste management hierarchy; i.e. minimisation, re-utilisation, recovery and disposal (Defra, 2007a). The water industry also recognises a significant cost advantage of agricultural recycling compared with alternative disposal routes such as incineration and landfill (Le, 2007). Costs-figures provided by United Utilities plc for 2006 indicated that agricultural recycling costs the company approximately £150 per tonne of sludge (dry solids basis, including finance and depreciation), and that landfill and incineration are approximately 30% and 60% more costly respectively.

In the North West region, United Utilities plc is responsible for approximately 16% of the total sludge output produced in England and Wales equivalent to *c*.215, 000 tonnes of sewage sludge per year (dry solids basis). This amount reduces to *c*.150, 000 tonnes per year (dry solids basis) after digestion (Whipp, 2007). The disposal strategy at United Utilities plc is based upon a dual approach of recycling to agricultural land (*c*.70%) and incineration (*c*.30%). Recycling to farmland, however, presents some difficulties which combine to restrain the agricultural route as well as the opportunities for increasing recycling targets in the long term.

Among the difficulties commonly encountered are; the variable chemical composition of biosolids (Sommers et al., 1976; Sommers, 1997), and the relatively poor understanding of the nitrogen availability following soil application (Bowden and Hann, 1997; Cordovil et al., 2007), the low N:P ratio of biosolids which is often recognised as an important factor affecting the build up of soil-P (Edge, 1999), land availability and farming practice (Moseley, 1999), the farmers' perception of biosolids (Reeves, 2007), the risk of heavy metals accumulation in the soil (López-Mosquera et al., 2000; Azevedo-Silveira et al., 2003) and their potential transfer on to the food chain (Obrador et al., 1997; Wang et al., 2003), and the (low) nutrients' concentration of biosolids which affect transport, storage, handling and spreading/field application.

On the other hand, a number of opportunities for recycling are also recognised. These arise from the increase in the price of mineral fertilisers recorded in recent years; e.g. the price of nitrogen in straight N-fertilisers increased from *c*.0.25 to *c*.0.60 £ kg^{-1} between 1994 and 2010 but it peaked £1.04 per kg [N] in 2008 and TSP (triple super-phosphate) increased from 100 £ t^{-1} to 315 £ t^{-1} during the same period but it reached 690 £ t^{-1} in 2008 (Nix, 1994-2010). This increase in the price of fertilisers combined with relatively weak grain prices (e.g. 90 £ t^{-1} for wheat [feed] – mean price for the period 1994-2010 [range 63-126 £ t^{-1}]; Nix, 1994-2010) have resulted in reduced profit margins to farmers; although, LIFFE's price for wheat (feed) for March 2011 is currently £205 per tonne (HGCA, 2011). Heffer and Prud'homme (2010) highlighted that demand for N, P and K is forecasted to increase at a rate of *c*.2-2.5% per year to 2014-15. These are important aspects which can give some room for lower cost fertilisers providing the issues highlighted above could be addressed. In addition, there is a need to make sustainable use of phosphates rock reserves which estimates indicated they are decreasing rapidly at present rates of extraction (Johnston, 2008; Hilton et al., 2010).

In response to the challenges being faced by the water industry, and to some extent, encouraged by those of the farming industry, a novel technique was proposed by United Utilities plc for the production of organomineral fertilisers (OMF) using biosolids granules. This new product concept would appear to be a sustainable alternative for the recycling of biosolids to land and it could contribute to overcome some of the problems highlighted earlier providing farmers a reliable organic-based product. Johnston (2008) referred to the recycling of organic materials to land and highlighted that the practice of recycling must provide a benefit to agriculture with no long term (undesirable) effects on soil fertility/productivity and be both environmentally and economically sustainable.

This present research was based upon the need to quantify the potential benefits associated with the use of OMF in agriculture. Therefore, the aim of this research was to determine the effects of the use of organomineral fertilisers (OMF) made from biosolids granules in winter wheat (*Triticum aestivum L.*) and rye grass (*Lolium perenne L.*) and to contribute towards the understanding of nutrient management and dynamics in agricultural systems, with particular regards to nitrogen and phosphorus. This aim was achieved through the five objectives defined in **Section 1.4.2** which addressed some of the critical issues of this product development; including agronomic, environmental, engineering and technical-economic related aspects while providing sound understanding of OMF management in cereal crops and grassland.

9.3 Product specification

The technique developed by United Utilities plc for the production of organomineral fertilisers through the coating of biosolids granules with urea and potash was used to formulate two fertiliser products with different nitrogen concentrations: **$\mathbf{OMF_{15}}$** (**15:4:4**) and **$\mathbf{OMF_{10}}$** (**10:4:4**). The formulation of the products was possible based on: **a.** chemical analyses of a typical sample of biosolids; **b.** standard nitrogen application rates in winter wheat crops (e.g. RB209 – MAFF, 2000; Brentrup and Link, 2004; Johnston and Poulton, 2009 – Broadbalk Experiment); **c.** phosphate and potash application rates in cereal crops; and **d.** technical guidance given by United Utilities plc.

With the exception of urea, the physical characteristics and the chemical composition of the fertilisers used in the experiments varied between the years. The material delivered did not exactly match the specified formulations (the N-concentrations in the products were in the range of 9.83% to 16.05% for OMF_{15}, and 7.15% to 10.52% for OMF_{10}).

Exceptions were those produced for 2008 and also for 2009 although in this later batch the OMF_{15} had 14% N. The particle size and size distribution also differed between years and from that of urea. For both OMF_{10} and OMF_{15}, particles were in the range of 0.60 to 37 mm in diameter whereas for urea the particle size range was between 0.60 and 5.50 mm. The relatively low physical quality and the variable chemical composition affected the agronomic performance of the fertilisers (this point will be discussed later in **Section 9.5**). Fertiliser particle size and size distribution are important characteristics affecting uniformity of distribution (Hofstee, 1993) and it is well documented that uneven spreading of fertilisers can result in undesirable consequences to the environment, the performance of the crop and ultimately profit margins (Dilz and van Brakel, 1985; Miller, 1996; Miller and Parkin, 2005; Miller et al., 2009).

As highlighted in **Chapter 1**, fertiliser spreading tests (ASAE, 1999) were to be conducted in the field using standard spreading equipment (spinning disc fertiliser spreaders) to aid in the optimisation of the physical properties of OMF in relation to their distribution uniformity. This study would also aim at determining the spreading requirements for the products; e.g. forward speed, machinery calibration and settings, with a view to optimising OMF application. Such tests could not be conducted since the pilot granulator had to undergo further adjustments and design-optimisation, and as a result, sufficient quantities of OMF with the required quality could not be produced for spreading trials. However, improvements in the physical and chemical quality of the products were made later in the project (2010) and these were recorded and reported (**Chapter 3**).

In order to address the objective of this research related to the study of the spreading characteristics of OMF, and given the difficulties encountered in conducting the spreading tests, a mathematical model was developed (**Chapter 4**). This trajectory model allowed predicting the distance at which individual fertiliser particles projected from a spinning disc land on the soil. The work builds upon earlier studies on the subject (Miller, 1996; Grift et al., 1997; Parkin et al., 2005). A distinctive feature of the model, which could not be found in the literature relating to fertiliser particle aerodynamics, is that it uses a drag coefficient (C_D) which is calculated for every instant in the particle's trajectory considering C_D as a function of the Reynolds number (*Re*). Measurement of some physical properties of the fertilisers used in 2010 allowed feeding the model to calculate the distance at which individual particles landed on the soil, given certain conditions: **a.** launch angle and height above the ground; **b.** initial velocity of the particle; **c.** particle diameter; and **d.** particle density.

Based on the results of the model, it can be stated that the spreading of OMF and biosolids may be possible to perform at tramlines between 12 m and 18 m depending on the machinery settings (launch angle, initial velocity of the particle and height above the ground), the shape of the distribution pattern, and the particles' characteristics (particle density and size range). In addition, to be able to match the minimum and maximum landing distances of urea (for particle diameters in the range of 1.00 mm to 5.00 mm), the range of particle sizes required for OMF_{10} and OMF_{15} would be approximately 1.10 mm to 5.50 mm and 1.05 mm to 5.30 mm, respectively; according to the range of particle densities (ρ_p =1300 to 1500 kg m^{-3}), launch angles (0° to 10°), and initial velocities (20 to 40 m s^{-1}) investigated with the model. The effects of particle diameter and particle density on the landing distance of individual particles were shown. A series of tables of particle diameter versus particle density were produced which would enable predicting the basic requirements for OMF to be able to achieve a particular spreading width. This was based on the approach of Parkin et al. (2005) and it requires confirmation with experimental data. Special attention should be paid to producing the correct particle size range and to achieve a granulometric spread index (GSI, %), ideally, not greater than 15% to prevent from significant segregation (Miserque and Pirard, 2004).

The compression tests conducted on individual particles showed that OMF particles start to deform when relatively low forces were applied. Interestingly, OMF particles did not show a breaking force that induced the fracture of the particle; on the contrary, they tended to deform under pressure and behaved in a plastic way. Hignett (1985) highlighted that the breaking force of urea must be greater than 15 *N* to avoid particle fracture during handling. Particles' deformation started immediately after a relatively small force was applied and they were fully compressed before reaching 15 *N* which was the reference's (lower) value indicated for urea to avoid particle fracture (Hignett, 1985). This was attributable to both the organic nature of the material and the moisture content (10.77% for biosolids, 14.95% for OMF_{10} and 17.34% for OMF_{15}). The samples of urea tested showed breaking forces well above the lower limit suggested by Hignett (1985) with values in the range of 23 to 32 *N* depending on the particles' diameter. On the other hand, the relatively low particles' strength in the OMF indicated that they were likely to deform under pressure. This can influence their aerodynamic properties ultimately affecting the landing distance during spreading. It is recommended that moisture content is maintained to a minimum (e.g. $\leq$10%) so that their pseudo-spherical shape is not affected during handling and storage; plastic packaging should be considered for storage and transport. Lower moisture contents than 10% could bring about increased cost of energy in drying of the granules.

In addition, particle strength can also alter the particle size distribution if particles undergo fracture which can affect the spreading pattern if segregation takes place (Bradley and Farnish, 2005). The proposed trajectory particle model requires validation with data obtained experimentally using standard test procedures such as that specified in ASAE (1999). A recommendation can be made to measure distribution uniformity and conduct the calibration of a standard broadcast spreader once sufficient quantity of the right quality OMF granules are produced. The experimental data should be used to validate the model, determining the spreading requirements of the material and further improve the physical characteristics of the particles.

With regards to the proposed formulations for the two OMF products, it was argued in **Chapter 3**, that higher concentrations of nitrogen are technically possible but increasing the proportion of mineral nitrogen (and potassium) can have some potential drawbacks. Firstly, there may be an associated increase in the manufacturing costs which can arise from sourcing larger amounts of urea needed for the coating of base biosolids granules. Secondly, the production (and commercialisation) of more concentrated nitrogen products can compromise the final amount of biosolids recycled through agriculture. Equally, if the nitrogen concentration in the product was to be increased, the land-bank required for agricultural recycling would need to be expanded accordingly to be able to meet the same disposal targets to that of biosolids. Estimates suggested that the required land-bank for OMF_{15} would need to be approximately 1.7 times larger than that of OMF_{10} assuming OMF-N was applied at a rate of 225 kg [N] ha^{-1} and that the price of the nitrogen was equivalent to that of urea-N.

By contrast, an increase in the concentration of nitrogen in the OMF above the proposed 15% N could also result in increased acceptance of the product allowing for reductions in the cost of transport and storage, handling and spreading and also for improvements in the work rates. However, it appears to be unlikely that such increase in acceptance/demand of the product would be sufficient to compensate for the reduction in the volume of biosolids disposal as with lower nitrogen concentrations. Increased nitrogen concentration in the OMF will required an increase in the price of the product which could make alternative nitrogen sources become more attractive at a higher price of OMF-N. The economic analyses conducted in **Chapter 8** suggested that the price of the OMF would be closely linked to the price of nitrogen. Therefore, an increase in the content of N in the OMF will result in increments in its price which can lead to a reduction in the demand of OMF and consequently its substitution by alternative N-sources.

The information reviewed in the literature could not identify work conducted in the past or being undertaken on the use and application of OMF products on cereal crops and grassland derived from the coating of biosolids granules with urea and potash. There is, however, substantial amount of work reporting experiences in the use of nutrient-enriched organic-based materials. These include for example mixtures of industrial by-products with mineral fertilisers (Graziano et al., 2008), granulated mixtures of compost materials with addition of phosphate fertilisers and peat (Paré et al., 2009) or composted pig slurry (Paré et al., 2010a-b), mixtures of mineral fertilisers and peat (Richards et al., 1993; Tejada et al., 2005) and manure (Buondomo et al., 1997; Zebarth et al., 2005).

There is also a registered process (WIPO, 2009) for the production of a compound-granular OMF made from organic by-products of the sugar and alcohol industries. The process differs from that of OMF_{10} and OMF_{15} in that there is no coating of the granule with urea and potash. Instead, by-products are bulked up with mineral fertilisers to finally produce a particle containing both organic- and mineral-fractions in the same granule. United Utilities plc has informed that a patent for the process of production of OMF is ongoing work and it understands that the findings coming from this research will help to support the application for the patent. In addition, there is a related patent application (US7504035 B2) assigned to United Utilities plc (2009) for the treatment of putrescrible cakes for the reduction of *Escherichia coli* and odour which are also required in the product.

The methods available for the land application of biosolids were reviewed in **Chapter 2**. In general, biosolids can be surface-applied, and where possible, followed by incorporation, or they can be injected into soil using deep or shallow injection techniques. The injection of biosolids is considered to be a superior technique compared for example with splash plate spreaders and dribble bars. Some of the early work on the injection of biosolids includes that conducted by Smith et al. (1973) and also the research concerning the design of injector tines (e.g. Warner and Godwin, 1988; Warner et al., 1991; and more recently Pullen et al., 2004b). Shallow injection techniques (≤150 mm) were shown to be relatively more efficient in reducing ammonia emissions and energy requirements compared with deep (150-450 mm) injection techniques (Phillips et al., 1990; Hann et al., 1992; Moseley, 1999). The costs of injection of biosolids, as reported by Nix (2010), are approximately £51.75 per hour whereas for slurry-spreading these are £35.75 per hour (tanker) and £58.40 per hour (umbilical hose) for work rates between 6 to 10 hectares per day (assuming similar work rates to subsoilling but without considering the time required for re-filling the tanker).

Costs of spreading FYM (as reference for spreading of biosolids in the form of cake or with higher dry-solids content) are reported (Nix, 2010) to be approximately £36 per hour (tractor and spreader) and £30 (tractor and loader). One of the advantages of granular fertilisers, including granular OMF, is that they can be applied using standard spreading equipment; typically, spinning disc fertiliser spreaders. Dampney et al. (2003) highlighted that this type of equipment has relatively low capital cost and high versatility making it capable of operating with reasonable accuracy in tramlines of up to 24 m apart thereby providing relatively high work rates (up to 30 to 40 hectares per day). Based upon cost-figures reported by Nix (2006-10), estimates of costs of spreading (farmer's cost) for biosolids granules, OMF_{10} and OMF_{15}, and assuming application at the optimum nitrogen rate and using broadcast spreaders, were **£78.03**, **£44.91**, and **£31.20 per hectare** respectively on average for 2006-07 to 2009-10.

The spreading cost of urea, also on average during the same period, was estimated at **£14.65 per hectare** (contractor's charge for spreading was estimated to be approximately 35-37% higher than farmer's costs for the same range of tonnage for all fertiliser materials between 2006-07 and 2009-10). Therefore, there is an opportunity for farmers to make a reduction in the cost of spreading with the use of OMF compared with biosolids granules. These differences are greater when comparing with liquid sludges requiring injection, according to the costs highlighted earlier. The production of OMF in the form of dry-granules having consistent physical characteristics and similar to those of standard mineral fertilisers represents a significant advancement in terms of their spreading requirements compared with traditional methods of application of biosolids.

The following section reviews the results obtained in the incubation studies; these provided a better understanding of nutrient release characteristics of OMF in comparison with mineral fertilisers. An effort was made to use the data to predict the behaviour of the fertiliser in-field conditions.

9.4 Nitrogen and phosphorus availability

The results of the incubation studies for nitrogen showed that the largest increase in SMN was observed in the first sampling event conducted 30 days after the start of the experiment (**Table 9.1**). This effect occurred consistently in the three sets of incubation trials conducted for the assessment of the availability of OMF-N. The table presents the mean values of SMN obtained for OMF_{15}, urea and the unfertilised control averaged for the two soil types and nitrogen rates used.

The data shown in the table provides an indication of the relative levels of SMN likely to be encountered for each fertiliser material under the specified experimental conditions. These results demonstrated that the largest release of nitrogen occurs within 30 days from the start of the experiment. For the soil amended with OMF_{15}, the recorded increase in SMN was attributed to the rapid release of $NH_4^+ - N$ from the fraction carrying urea. The data shown in the table is presented to emphasise this effect; it may appear, however, from the values obtained at 90 days that both fertiliser materials resulted in similar levels of SMN but it is important to note that these correspond to the mean values obtained from the two soil types and nitrogen rates investigated.

Table 9.1: Mean values of SMN recorded for the three sets of incubation trials conducted. The values were averaged for the two soil types (clay loam and sandy loam) and the two nitrogen rates used (150 and 300 kg [N] ha^{-1}) in the experiments [(LSD$_{[5\%\ level]}$ =9.12 (max.rep); LSD$_{[5\%\ level]}$ =11.17 (max-min.rep); LSD$_{[5\%\ level]}$ =12.89 (min.rep); p<0.001; n=16 except control n=8 and initial level n=3].

	------------------------ SMN (mg [N] kg^{-1}) ------------------------		
Time/Treatment	**Control (N=0)**	**OMF_{15}**	**Urea**
0 (mean initial level of SMN)	22.8	22.8	22.8
30 days	72.8	124.5	157.7
60 days	100.3	148.3	174.4
90 days	102.0	166.1	168.2

In general, the availability of nitrogen at 90 days (as percentage of the total nitrogen applied) was found to be consistently lower (*c*.14% to 24% lower) in OMF_{15}-treated pots compared with those treated with urea. An exception to this was the clay loam soil amended with OMF_{15} at the equivalent rate of 150 kg [N] ha^{-1} which yielded approximately 30% more SMN at 90 days than the treatments receiving urea. This effect was not observed at 30 and 60 days respectively where SMN levels in urea-treated pots (as percentage of total nitrogen applied) were between 30% and 40% higher than OMF_{15} respectively (values of nitrogen available as percentage of the total nitrogen applied were 40.45% and 35.58% for OMF_{15}, and 81.64% and 65.80% for urea at 30 and 60 days respectively). Differences of the same order of magnitude were observed for all other treatments at 30 and 60 days respectively.

The chemical analyses conducted in the fertiliser materials in 2009 showed that the composition of OMF_{15} was approximately that of the specification containing 13.96% N and that biosolids had 3.97% N.

This means that approximately 72% of the total nitrogen in the OMF_{15} was urea-N and that the remaining 28% corresponded to the biosolids' organic-N. The data presented earlier in **Figures 5.3a-b** showed that the percentage of nitrogen available increased in relation to the nitrogen application rate. It also appeared that the increase in the availability of nitrogen was determined by the content of urea-N in the fertiliser (on average for the duration of the experiment). This is explained as the differences encountered in the nitrogen available (as percentage of the nitrogen applied) between the two fertilisers within the treatments were consistent for all treatments. This suggested that the organic-N fraction in the OMF_{15} had a limited contribution to the total nitrogen available when expressed as percentage of the total nitrogen applied. It can be argued that a determination of SMN at a shorter time interval than 30 days immediately after the start of the experiment would have been advantageous to provide a clearer indication of the rate of nitrogen release following soil application of OMF_{15} and urea.

Soil temperatures recorded in 2008 and 2009 at the lysimeters' station (College Farm, Silsoe) were useful to calculate the accumulated thermal time between 1 March and 30 June which is the time that coincides with the main growth period of winter cereal crops. Based on the work of Smith et al. (1998), it was possible to use the accumulated thermal time, as determined in the incubators, to correlate the information obtained in the laboratory with that of the field. The estimated accumulated temperature for this period in-field condition was 1593 dºC which was reached in the incubators at approximately 60 days from the start of the experiment. At this point, the net amounts of SMN for OMF_{15} amended-pots in the clay loam soil were equivalent to 19.5 and 82.7 mg [N] kg^{-1} respectively (or 47.5 and 201.8 kg [N] ha^{-1} respectively). For the sandy loam soil, the OMF_{15} after 60 days from its application yielded 56.3 and 68.8 mg [N] kg^{-1} when applied at 150 and 300 kg [N] ha^{-1} respectively (or 56.3 and 184.2 kg [N] ha^{-1}). Therefore, and acknowledging the extrapolation of the data, this is an indication that OMF_{15} has some potential to supply nitrogen to the crop, particularly, when applied at larger rates than the equivalent to 150 kg [N] ha^{-1}.

However, it was also noted that at 90 days, the accumulated thermal temperature in the incubators was 2250 dºC and that at this point, the percentage of nitrogen applied that became available from the OMF_{15} was found to be between 68% and 79% depending on the soil type and the nitrogen rate used. This suggested that there was still a significant amount of OMF-N, possibly, organic OMF-N, which had not undergone mineralisation.

The accumulated thermal temperature of 2250 dºC is likely to be reached in early August in-field conditions, according to the temperature records obtained in the lysimeters, which suggested that mineralisation of organic OMF-N, would progress beyond crop's senescence carrying nitrogen onto the following autumn sown crop. Hence, the timing of application of OMF in the spring has implications upon nitrogen management requiring fertilisation strategies that consider the crop rotation. It appears that the advantage of applying OMF in early spring; i.e. coinciding with the first nitrogen dressing in cereal crops – typically during March – is that it would provide the opportunity for the organic OMF-N fraction to undergo a more complete mineralisation during a longer period of time and to match the required thermal time before the harvest of the crop.

On the other hand, evidence coming from the studies conducted in the field (crop season of 2006-07) indicated that crop yield in OMF-fertilised plots reached similar levels to those fertilised with urea when the first nitrogen dressing in March was performed with a mineral (straight) nitrogen source using 100 kg [N] ha^{-1} in the form of UAN (33% N – solution) and the second nitrogen application (17th May) using OMF. It may be argued that, overall, crop yield was sustained in all fertilised plots as a result of the total nitrogen load applied (plots received the nitrogen rate as specified by the treatment and also the application of UAN in the first dressing). However, the use of mineral nitrogen (1st N-dressing) and OMF (2nd N-dressing) does provide a valuable indication of enhanced crop performance when both nitrogen sources are combined as part of the nitrogen fertilisation strategy.

There are also logistics advantages in applying OMF in the second dressing as soil conditions for traffic usually improve towards the summer. The most appropriate timing for application of OMF-N requires further investigation but attempts will be made to address this point later in this section when discussing the results obtained in the field studies. In addition, and based on the results of the incubation studies, if OMF-N was to be applied in the second N-dressing, soil sampling for determination of SMN is recommended prior to establishing the following crop in the autumn; e.g. oilseed rape. MAFF (2000) indicated that nitrogen may be applied in the seedbed to winter oilseed rape crops (sown in August-September) for SNS indexes 0, 1 or 2 at nitrogen rates of up to 30 kg [N] ha^{-1} to aid in the rapid establishment of the crop. Therefore, residual OMF-N should be accounted for, by means of soil analysis, prior to establishment of oilseed rape as there may be an opportunity for reducing nitrogen inputs in soils showing low SNS indexes.

The incubation experiments conducted for the assessment of phosphorus availability following application of OMF_{15} and SSP (single superphosphate, 18% P_2O_5) demonstrated that, overall, soil extractable-P levels in the unfertilised control was not significantly different from the soil amended with OMF_{15} (mean values were 79.66 and 80.01 mg [P] kg^{-1} [soil] for the control and OMF_{15}-treated soil respectively; $LSD_{[5\% \text{ level}]}$ =1.29). This result reflected the relatively low solubility of inorganic-P fractions present in the OMF_{15}. In this respect, Farrant et al. (2008) highlighted that at United Utilities plc the main process for phosphorus removal is by means of precipitation with $FeCl_3$ with the phosphorus removed being subsequently incorporated into the sludge. This results in the formation of Fe-phosphates which are mostly unavailable for plant uptake. Previous works (de Haan, 1980; Lu and O'Connor, 2001; O'Connor et al., 2004) had also highlighted the effect of precipitation in reducing the bioavailability of P.

In particular, the work of O'Connor et al. (2004) reported that the phyto-availability of biosolids-P that had undergone removal by precipitation was found to be significantly lower than 25% of that corresponding to triple-superphosphate (47% P_2O_5). Their findings appeared to be in close agreement with the results reported in **Table 5.4** (values of phosphorus available, as percentage of total-P applied for OMF_{15}-treated soils between *c*.-5.6% and 6.4%). In general, the percentage available phosphorus, relative to the total-P applied, was found to be greater in the sandy loam soil, despite the values of soil extractable-P in the clay loam soil were overall significantly higher than the sandy loam soil (mean values of 86.3 and 80.5 mg [P] kg^{-1} respectively; $LSD_{[5\% \text{ level}]}$ =0.95). Following these observations, it could be stated that the effect of OMF_{15}-P on the crop in the year of application is unlikely to be significant upon the yield of the crop given the low availability recorded (relative to the phosphorus applied), especially on the clay loam soil.

Interestingly, in both soil types and including the unfertilised control soils, there was a change in the soil-P index as recorded at the end of the 90 days incubation trial compared with the initial soil-P index (in all treatments soil-P index changed from 5 – initial level – to 6 – end experiment). Soil-P indexes 5 and 6 correspond to values of soil extractable-P in the range of 71 to 100 and 101 to 140 mg [P] l^{-1} respectively (MAFF, 2000). For the control soils the change in the level of soil extractable-P was marginal, *c*.+7 mg [P] l^{-1} above the initial levels recorded in both soil types (97.5 and 96.9 mg [P] l^{-1} for the clay loam and the sandy loam respectively). This effect may be explained as a result of mineralisation/release of soil-P contained in the SOM and although small, it was sufficient to induce a change in the index.

The change in soil-P status in OMF_{15}-treated soils was of similar order of magnitude to the controls and that was observed regardless of the phosphorus application rate used (mean values between 102.3 and 105.1 mg [P] l^{-1} at the end of the experiment). This was therefore consistent with the observations made earlier, that the effect of OMF_{15}-P upon the yield of the crop may not be significant in the year of application.

The magnitude of the changes observed in soil extractable-P levels in OMF_{15}-treated soils in the incubation studies were consistent with those reported for the glasshouse and the field studies but the effect should be investigated in the longer term to be able to identify a possible trend. In this respect, Johnston and Syers (2006) highlighted that P contained in the fertilisers is not irreversible fixed following soil application but the critical levels in the soil may be maintained by replacing, annually, the equivalent amounts to those taken off by the crop.

These authors suggested that the amount to replace can be estimated from the percent recovery of applied phosphorus using the balance method; i.e. P removed with the crop relative to the total P applied. The increase in soil-P levels recorded in SSP-treated soil was expected as a result of the larger solubility of the P present in the source (92-94% water soluble phosphorus; Richards, 2002). The overall differences in the phosphorus available (relative to the total-P applied with the fertilisers) recorded between the two soil types may be attributable to the content of clay and SOM. In general, P-adsorption increases in soils with higher content of clay (Sanyal and De Datta, 1991) and they require the application of larger amount of P-fertilisers to increase the availability of soil-P to the crop compared with coarser textured soils (García et al., 2005). Similarly, the increase in P-adsorption is associated to the increase in SOM although adsorption to it has relatively low binding energy (García et al., 2005).

Smith et al. (2002) investigated plant available phosphorus in an incubation study using thermally-dried pellets and biosolids granules. The authors reported that high temperature-drying significantly decreased the extractable-P concentration in the sludge (e.g. by 20-60% compared with dewater digested cake) and that P-release from thermally-dried biosolids declined further with iron enrichment. This also supports the observations made for OMF_{15}-P which resulted, overall, in consistently lower values of soil extractable-P than the standard P-fertiliser. The study of phosphorus availability following soil application of OMF_{15} demonstrated that phosphorus contained in the product did not influence significantly soil-P status despite the change (increase) recorded in soil-P index.

In agreement with Johnston and Syers (2006) the replenishment of soil-P that has been taken off with the crop at harvest, by means of application of P-containing fertilisers, is necessary to restore the soil-P status and to maintain it above the critical levels required for the soil-crop system; e.g. at/above the target soil-P index. This may be achieved by OMF-fertilisation and it was shown in the field studies (**Chapter 7**) that OMF applied to the experimental plots contributed to maintain soil-P levels as they remained close to constant over the range of application rates. It is acknowledge that the observations made after these incubation studies are bound by the experimental scale but the findings appeared to correlate well with those obtained when the experiments were scaled-up in the field.

9.5 Agronomic characteristics and practical aspects of OMF application

The studies conducted in the glasshouse with pots-grown rye grass showed that dry matter yield responded linearly to the application of nitrogen in the range of nitrogen rates investigated (0 to 300 kg [N] ha^{-1}) which was in agreement with earlier work reported in the literature (e.g. Reid, 1970; Sparrow, 1979; Morrison et al., 1980). The use of linear functions to describe the relationship between dry matter yield and nitrogen application rate showed acceptable fits ($R^2 \geq 0.75$) of the linear models. A summary of the results of annual dry matter yield encountered for the grass grown in the glasshouse is shown in **Table 9.2**. The results shown in the table correspond to the mean values of dry matter yield for the two nitrogen rates used.

Table 9.2: Annual dry matter yield (kg [DM] ha^{-1}) of pots-grown rye grass between 2007 and 2009 – The values shown correspond to the mean for the two nitrogen application rates used except for the unfertilised controls [LSD$_{[5\%\ level]}$ =734.6 (min.rep), LSD$_{[5\%\ level}$ =636.2 (max-min.rep), LSD$_{[5\%\ level}$ =519.4 (max.rep); p=0.045); n=6 except control n=3].

Clay loam soil	------------------------ Dry matter yield (kg [DM] ha^{-1}) ----------------------				
Year/Treatment	**Control (N=0)**	**Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**
2007	3713	5941	6819	7632	9305
2008	3700	5265	6008	6052	6954
2009	3194	5352	5399	5546	5276
Sandy loam soil	------------------------ Dry matter yield (kg [DM] ha^{-1}) ----------------------				
Year/Treatment	**Control (N=0)**	**Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**
2007	2279	5285	5932	6667	8095
2008	3526	6009	6178	6119	6211
2009	3265	5005	5123	5420	5421

As can be read off the table, the differences observed between the treatments were, overall, significant ($p=0.045$). In addition, annual dry matter yield varied within-treatments and between-years for the same treatment. In general, there was a decrease in the level of dry matter produced in 2008 and 2009 compared with 2007 (exception to this were the yields recorded on average for biosolids and OMF_{10} in 2008 compared with 2007). However, it is worth noting that the growth period between the 2nd and 3rd cuts in 2008 was 20 days longer than that of 2007 which provides some explanation to the relatively larger accumulation of dry matter in year two. The magnitude of the reduction in biomass production appeared to be related to the concentration of urea-N in the fertiliser and the extent of the decrease in the yield being greater in the clay loam compared with the sandy loam soil. In addition, there was an effect of the rate as the pots that received 300 kg [N] ha^{-1} showed comparatively a larger decrease in biomass yield compared with those treated with 150 kg [N] ha^{-1}.

The regression analyses undertaken indicated that a similar trend was also observed in the responses to the application of nitrogen, as determined by the increments in dry matter yield per kg of additional N. In 2007, the range of responses obtained for OMF_{10}, OMF_{15} and urea were between 14 to 26 kg [DM] ha^{-1} per kg of additional N which were found to be in agreement with typical responses (15 to 30 kg [DM] ha^{-1} per kg of additional N) reported in the literature for similar nitrogen application rates (e.g. Morrison et al., MAFF, 2000; Fisher and Jewkes, 2009).
In 2008 and 2009, however, all treatments (except biosolids) showed relatively similar increments in dry matter yield per kg of additional N (range of 6.5 to 11.2 kg [DM] ha^{-1}). The use of biosolids resulted; overall, in relatively lower but more consistent responses between-years in the range of *c*.7 to 12 kg [DM] ha^{-1}.

It was argued that the overall reduction in the responses to applied nitrogen and total dry matter yield between the year of establishment and the subsequent two years was possibly due to the surface-application of urea-containing fertilisers and the air temperatures recorded inside the glasshouse. The mean temperature recorded (Ghalamboran, 2011) on the date the fertilisers were applied in 2009 was 24.3°C (range of 17.2°C to 32.8°C) which were possibly linked to losses of nitrogen by volatilisation of ammonia enhanced by their application on the surface. The effect of the temperature upon the increase in the losses of nitrogen by volatilisation following surface application of urea-containing fertilisers is well documented (e.g. Kumar and Wagenet, 1984; Watson, 1987; Campos-Bernardi et al., 2010) and also its relationship with the nitrogen application rate (e.g. Cookson, 1999).

It is important to highlight that overtime, dry matter yield, in all treatments, tended to stabilise at a level comparable to that of the pots that had received biosolids. It appears therefore that the prevailing experimental conditions in the glasshouse, benefited the mineralisation of organic-N contained in both biosolids and OMF; hence, sustaining dry matter yield overtime. This effect was not observed in the field where temperature and soil moisture conditions were often suboptimum to favour a more complete mineralisation of the organic-N fraction. Following these observations, it was recommended that given the impossibility of incorporating OMF in a grassland situation (except during seedbed preparation – spring sown grass), the fertiliser should ideally be spread with favourable meteorological conditions; especially, temperature and rainfall. The occurrence of moderate amounts of rainfall (e.g. up to 20 mm) following application of urea-containing fertilisers has been reported to reduce losses of nitrogen by volatilisation by favouring its incorporation into the soil (Darwich, 1998; Echeverría and Sainz-Rozas, 2005).

The current research did not conduct studies to investigate the optimum timing for application of OMF on grass crops for which strong recommendations cannot be given in this regard. The same is true with respect to how the applications should be split during the season. Therefore, further research is required to determine both the optimum timing of fertiliser application and the recommended application rate in each split. This should be determined in relation to the particular characteristics of the production system. However, the general guidance for the fertilisation of grass crops, as given in RB209 (MAFF, 2000), may be followed taking into account some of the elements reported in this work. It was reported that early application of OMF (e.g. late February to early March) would favour a more complete mineralisation of the organic-N fraction during the spring and summer season. Later applications may be less critical than in cereal crops because grass continues growing well into the autumn which, to some extent, can reduce the chances of leaching from applied OMF-N. The study of Delin and Engström (2010) suggested that the application of organic-based fertilisers should be conducted at least 30 days prior to the peak of nitrogen uptake by the crop to maximise nitrogen use efficiency. This observation is consistent with the recommendations for the application of nitrogen to grass given in RB209 (MAFF, 2000) which are not conducted later than August. The work of Anslow and Green (1967), highlighted that the maximum growth rate in perennial rye grass (kg [DM] ha^{-1} day^{-1}) occurs in May and it is followed by a decline in the rate of accumulation of dry matter in June, and by a second but smaller peak of growth in July. The overall decline in dry matter yield and NUE overtime can also be explained by the relatively late timing of fertiliser application in 2008 and 2009.

These were conducted in late May/early June following the first cut of the grass in years two and three of the experiment. The application of the fertilisers should have been conducted in March/April in order to match the application of the fertiliser with the requirements of the grass. However, there was also a need to determine possible residual effects from previous fertiliser applications up to the first cut (prior to the application of N in 2008 and 2009) which also needed to be assessed during the maximum growth period to be able to detect differential effects in dry matter yield as a result of the fertiliser type. In addition, split applications of nitrogen are generally more effective in increasing annual dry matter yield than single-heavy nitrogen dressings (Castle and Reid, 1968). The number of splits should be adjusted according to the requirements of the system whether grazing or other. Given the linear responses encountered in the glasshouse up to a rate of 300 kg [N] ha^{-1} it is difficult to provide an optimum nitrogen application rate. However, it is reasonable to state that responses at higher nitrogen rates may be expected; therefore, the recommendations given in RB209 (MAFF, 2000) for grazing – dairy cows, and grass for silage (total nitrogen loads in the range of 300 to 380 kg [N] ha^{-1} per year for SNS high to low respectively) regarding the timing and splits of the applications can be followed. Other grass systems (e.g. grass for hay production) generally require lower nitrogen rates which approximately fall within the range of nitrogen application tested in the glasshouse. In these situations, the recommendations given in RB209 may also be applicable to OMF-N. It is also possible to state that the application of OMF should be done on the basis of the nitrogen requirement but for situations with soil-P index above 3, the total nitrogen load should consider a straight nitrogen source in addition to OMF-N as part of the fertilisation programme.

The N:P ratios in both OMF products are relatively high to result in over-application of phosphorus in the range of nitrogen rates given in RB209 – maximum of 380 kg [N] ha^{-1} per year for grazing (dairy cows) at SNS low which would result in 100 kg [P_2O_5] ha^{-1} with OMF_{15} and 150 kg [P_2O_5] ha^{-1} with OMF_{10} at this nitrogen level (assuming 4% P_2O_5). These levels of phosphate fertilisation should not encourage (in the short term) an increase in soil-P index given the low availability of OMF-P when working on soils at/below index 3 (soil-P index 2 requires a total phosphate load of 90 kg [P_2O_5] ha^{-1} per year for maintenance; MAFF, 2000), and instead, they can contribute to replenish off-take. In the longer term, however, the potential effects derived from the continuous application of OMF-P are more difficult to predict as they could not be assessed in the time-scale of this project.

However, the findings coming from both the studies in the glasshouse and the field showed that even when working on a soil at P-index 5, the index did not change significantly and that soil status remained at approximately the same level as that recorded at the start of the experiment (see **Table 6.9** and **Figure 7.20** for the glasshouse and field studies respectively). The narrower N:P ratio of OMF_{10} compared with OMF_{15} makes it more suitable in situations of lower soil-P index but because its nitrogen concentration is also lower, if the total phosphorus load was reached, a straight nitrogen fertiliser source would be required.

MAFF (2000) also recommends splitting the application of phosphate and potash during the season for which their application strategies are compatible with that of nitrogen (although for potash a single application is also recommended). The application of potassium with OMF would not be in excess of that required for the soils at K-index 3; i.e. total K load of 130 kg [K_2O] ha^{-1} per year, or lower when nitrogen is applied to grass at the maximum recommended rate in RB209; i.e. 380 kg [N] ha^{-1}.

As for phosphorus, assuming 4% K_2O content in the fertiliser, the total load of potassium for the maximum rate of nitrogen (380 kg [N] ha^{-1} per year – grazing dairy cows) would be equivalent to 100 or 150 kg [K_2O] ha^{-1} depending on the use of OMF_{15} or OMF_{10} respectively. For K-indexes 0 and 1, supplementation with a straight K-fertiliser may be needed to maintain the index. A restriction for the use of OMF may arise when there is a known risk of hypomagnesaemia which requires avoidance of K-fertilisation in the spring (MAFF, 2000).

In general, nitrogen use efficiency (NUE) in the glasshouse studies as determined by the apparent recovery of applied nitrogen (R_N) showed significant differences between-years. Estimates of R_N in 2007 were found to be, on average, 29% (biosolids), 41% (OMF_{10}), 51% (OMF_{15}) and 75% (urea). The nitrogen recovery was associated to the nitrogen content in the fertiliser and also with the concentration of readily available nitrogen in the material. Overall, the results showed the same trend as that indicated for dry matter yield; R_N decreased markedly in year two of the experiment, and the extent of this decline was related to the content of urea-N in the fertiliser. In 2008, estimates of R_N were 20% (biosolids), (*c*.25% for OMF_{10} and OMF_{15}) and 31% (urea). This overall reduction in the recovery of nitrogen could be associated with the surface-application of the fertiliser thereby reducing N uptake and nitrogen use efficiency. Possible ways to increase nitrogen use efficiency with the use of OMF may include; where possible, soil incorporation of the fertiliser (seedbed – spring sown grass), and surface application with favourable climatic conditions as highlighted earlier.

Overall, there was a build-up of TN_{soil} (from 0.145% to 0.181% - sandy loam, and from 0.192% to 0.22% - clay loam) and SOM (mean increase of *c*.18%) which were found to be greater according to the content of organic-N in the fertiliser. This general build-up in the measured soil parameters appeared to be consistent with the results of dry matter yield whereby the increase in TN_{soil} and SOM resulted in larger amounts of SMN contributing to sustain dry matter yield. However, this effect could not be confirmed with the results of SMN which were very low both years (mean values of SMN between 4.2 and 5.5 kg [N] ha^{-1} equivalent for the sandy loam and the clay loam soil). It is important to emphasise that when operating within NVZ, relevant regulations must be observed (i.e. Nitrate Pollution Prevention Regulations 2008 Statutory Instrument 2008/2349). These impose a field limit of 250 kg [N] ha^{-1} per year – grazing livestock (or 170 kg [N] ha^{-1} per year average for the farm) for organic manures and include closed periods for the spreading of nitrogen (Defra, 2009d). The European Commission has agreed Defra's petition to allow farmers having >80% of the land as grassland to work above the required limit of 250 kg [N] ha^{-1} per year (Defra, 2009d).

A summary of the results of grain yield (winter wheat) and dry matter yield (rye grass) obtained in the field studies are shown in **Table 9.3**. The studies conducted in the field showed that in both crops urea generally outperformed biosolids, OMF_{10} and OMF_{15}. The average increases in grain yield (relative to that of biosolids-treated plots) over the four crop seasons in OMF_{10}-, OMF_{15}-, and urea-treated plots were 11.5%, 23%, and 42.4% respectively. For rye grass, these were approximately 22%, 33%, and 34% respectively. The results of the pilot investigation conducted in Avenue Field in 2006-07 showed that, overall, there were not significant differences ($p>0.05$) in grain yield with respect to the fertiliser type used. This was attributable to the use of UAN (33% N – solution) at a rate of 100 kg [N] ha^{-1} in the first dressing. The differences in grain yield were also nonsignificant ($p>0.05$) for comparisons between the nitrogen application rates. The application of urea, OMF and biosolids to the experimental plots was conducted on 17th May, approximately 3 weeks later than the 2nd nitrogen dressing of the adjacent commercial crop. Overall, the crop treated with OMF performed to a similar level of grain yield as that of urea. These results suggested that by splitting the application of nitrogen into two dressing (which is usually the standard practice in winter wheat receiving nitrogen rates ≥120 kg [N] ha^{-1}) and that by using a straight (mineral) nitrogen source in the 1st dressing at approximately 40-50% of the full rate, and subsequently, applying OMF in the 2nd dressing with the remaining 50-60% of the required nitrogen, crop yield should not be significantly affected.

It should be noticed that the MERN values obtained for OMF_{10} and OMF_{15} in 2006-07 were 274 and 248 kg [N] ha^{-1} for $P_N \approx P_{N\text{-Urea}}$. In the following crop seasons, the fertilisers were applied in full at the rates corresponding to their treatments for which the results obtained in the first season would require further investigation. However, they provided a valuable indication of the overall crop performance when mineral- and OMF-N are combined as part of the fertilisation programme.

Table 9.3: Grain yield (kg ha^{-1}) of winter wheat for the crops seasons of 2006-07 to 2009-10 and annual dry matter yield (kg [DM] ha^{-1}) of rye grass in 2009 and 2010 – The values shown correspond to the mean yield for entire range of nitrogen application rates used except for the unfertilised controls. ($LSD_{[5\%\ level]}$ values are shown below; n=14 except control n=4).

Avenue Field	-------------------------- **Mean grain yield (kg ha^{-1})** --------------------------				
Season/Treatment	**Control (N=0)**	**Biosolids**	**OMF_{10}**	**OMF_{15}**	**Urea**
[1]2006-07 (1st wheat)	6332	10325	10367	10498	10751
[2]2007-08 (2nd wheat)	3145	5869	7477	7010	8126
Chippies Field	-------------------------- **Mean grain yield (kg ha^{-1})** --------------------------				
Season/Treatment	**Control (N=0)**	**Biosolids**	**OMF_{10}**	**OMF_{15}**	**Urea**
[3]2008-09 (1st wheat)	4796	8931	9247	10416	10980
[4]2009-10 (2nd wheat)	1011	2911	4169	4489	5939
Avenue Field	------------------------ **Dry matter yield (kg [DM] ha^{-1})** ----------------------				
Year/Treatment	**Control (N=0)**	**Biosolids**	**OMF_{10}**	**OMF_{15}**	**Urea**
[5]2009 (Grass – year 1)	6188	9285	11270	11958	12230
[6]2010 (Grass – year 2)	2192	5394	6624	7385	7357

[1]LSD =1080.9 (max-min.rep); LSD =642.2 (max.rep); p=0.471 (use LSD =489.5 (biosolids vs. control); p=0.135). [2]LSD =1284.5 (max-min.rep); LSD =763.1 (max.rep); p<0.001. [3]LSD =1474.3 (max-min.rep); LSD =875.9 (max.rep); p<0.001. [4]LSD =857.3 (max-min.rep); LSD =509.3 (max.rep); p<0.001. [5]LSD =1048.7 (max-min.rep); LSD =623.0 (max.rep); p<0.001. [6]LSD =883.6 (max-min.rep); LSD =524.9 (max.rep); p<0.001 (Includes only two cuts).

Based on the results of the incubation studies, it is likely that this fertilisation strategy (OMF applied at the time corresponding to the 2nd nitrogen dressing) will result in some residual OMF-N after the harvest of wheat; possibly, from un-mineralised organic OMF-N. Therefore, it is recommended that soil analyses for determination of SMN were conducted prior to the establishment of the following crop. This will be of importance in oilseed rape crops requiring nitrogen in the seedbed; typically, in crops grown in soils having SNS 0, 1, and 2 which require nitrogen rates of up to 30 kg [N] ha^{-1} during establishment (MAFF, 2000). Residual OMF-N can contribute to reduce/avoid the application of nitrogen in the seedbed in oilseed rape following a winter wheat crop that has received OMF-N in the second nitrogen dressing but it should be verified by means of soil analysis.

In Avenue Field, the mean value of SMN at the time of harvest of the 2nd wheat (harvest of 2008) in OMF-treated plots was *c*.4.40 mg [N] kg^{-1} (equivalent to 11.8 kg [N] ha^{-1} assuming a depth of 0.2 m and soil bulk density of 1.34 t m^{-3}). For Chippies Field, the mean value of SMN at the time of harvest of the 2nd wheat (harvest of 2010) in OMF-treated plots was *c*.18.2 mg [N] kg^{-1} (equivalent to 46.9 kg [N] ha^{-1} for the same depth and soil bulk density). The higher SMN value recorded in Chippies Field was possibly due to the particularly drier conditions registered in the spring of 2010. The opportunities for reducing the nitrogen application rates in the spring are more limited as analyses of SMN conducted annually prior to the application of the fertilisers indicated that there were not significant differences ($p>0.05$) between the control plots and the treatments. Logistically, there also are appears to be an advantage in applying OMF at the time corresponding to the second nitrogen dressing (typically middle of April to early May; MAFF, 2000), since soils usually become drier towards the spring/summer being, therefore, less prone to damage by the effect of traffic on the field.

In the following crop seasons, the fertilisers were applied in full in a single dressing in late March to early April. The use of a single dressing was due to practical reasons associated with handling and spreading relatively small amounts of fertilisers on the plots. Overall, the statistical analyses revealed that for the harvest years of 2008 to 2010, there was a significant effect of the fertiliser type upon the yield of the crop (p-values <0.001). As shown in **Table 9.3**, grain yield was found to increase with the use of more concentrated nitrogen (available) sources; except in the 2nd wheat crop in Avenue Field where the yield obtained with the use of OMF_{10} was marginally higher than that of OMF_{15}. However, this effect was nonsignificant for an $LSD_{[5\%\ level]}$ value of 763.1 and it was possibly due to the physical quality of the materials applied, as recorded in **Chapter 3**.

The regression analyses undertaken indicated significant relationships (p-values <0.001) between the nitrogen application rate and crop yield when quadratic functions were fitted to the data; in general, the R^2 values showed acceptable fits to the quadratic models ($R^2 \geq 0.60$). However, it is important to note that for the data corresponding to the 2nd wheat crops, the estimates of the parameters for the square term (i.e. N rate square) for biosolids, OMF_{10} and OMF_{15} were nonsignificant (t_{pr}-values >0.05). When this term was removed from the model and it was converted to a linear one, the regression analyses remained significant for both the model and the linear term. This implied that the relationship between nitrogen application rate and crop yield in a second wheat crop fertilised with biosolids, OMF_{10}, or OMF_{15} could also be explained by a linear function for the range of nitrogen rates investigated.

By contrast, this effect was not observed for the data corresponding to urea which consistently showed significance for the square term. Since the coefficients for the square term were negative, quadratic functions were preferred which allowed deriving the terms Y_{max} (maximum grain yield) and N_{max} (nitrogen rate corresponding to the maximum yield). Most importantly, it allowed the calculation of the MERN (the most economic rate of nitrogen) and its corresponding Y_{MERN} (grain yield at MERN) needed for the gross margins analyses. On average, over the four crop seasons, the nitrogen rate required for maximum grain yield (N_{max}) with the use of biosolids was 247 kg [N] ha^{-1} (Y_{max} =7908 kg ha^{-1}) whereas for urea N_{max} and Y_{max} were 252 kg [N] ha^{-1} and 10425 kg ha^{-1} respectively. For OMF_{10} and OMF_{15} these parameters were found to be 306 and 292 kg [N] ha^{-1}, and 9226 and 9613 kg ha^{-1} respectively. These values provided an indication of the relatives efficiencies of the nitrogen applied for maximum yield. The reported values of N_{max}, and their corresponding Y_{max}, for the crop treated with biosolids, were used as equivalent to their optimum economic since it was assumed that the cost of biosolids-N to the farmer was zero.

Nitrogen use efficiency (NUE) in winter wheat, as determined by the apparent recovery (R_N), the agronomic efficiency (A_E) and the partial factor productivity (I_P) of applied nitrogen are shown in **Table 9.4**. The values shown in the table correspond to the mean values of NUE for the entire range of nitrogen application rates used in the field studies. R_N was determined for 2006-07 and 2007-08 (1st and 2nd wheat – Avenue Field) as analyses of TN_{grain} were only conducted for the first two years of the field experiments. In general, grain yield and NUE were increased when the concentration of readily available nitrogen in the fertiliser was increased; an exception was the use of OMF_{15} compared with OMF_{10} in 2008 which resulted in relatively lower NUE for all indexes. As highlighted earlier, this could be attributable to poorer physical characteristics of OMF_{15} compared with OMF_{10} (**Chapter 3**). In addition, there was not an apparent enhancement in NUE, as a result of NPK fertilisation with OMF in comparison with N alone for an already satisfactory soil-P and -K status.

Milford and Johnston (2007) highlighted that soil-K status has a significant effect in enhancing both nitrogen uptake and response to nitrogen. The authors indicated that the yield response to applied nitrogen fertiliser decreases markedly by low concentrations of soil exchangeable-K (low soil-K index). This synergism between nitrogen and potassium was not evident from the combined application of both nutrients in the OMF since soil-K levels in Avenue and Chippies Fields were already satisfactory. However, it was expected that the application of K with the OMF had contributed to maintain the indexes while in arable cropping.

For all indexes, NUE tended to decrease with the increase in the nitrogen application rate which was in line with the shape of the response curves; i.e. the increment in yield with respect to the control is progressively smaller as the nitrogen rate is increased.

Table 9.4: Nitrogen use efficiency (NUE) in winter wheat as determined by apparent recovery (R_N), agronomic efficiency (A_E) and the partial factor productivity (I_P) of applied nitrogen – Mean values obtained over the entire range of nitrogen application rates used (50-250 kg [N] ha^{-1}; except 2006-07 which received additional N as UAN (33% N – solution) at 100 [N] ha^{-1}) [*SD*: standard deviation; n=14].

2006-07	---------- **Fertiliser type** ----------							
NUE	**Biosolids**	***SD***	**OMF$_{10}$**	***SD***	**OMF$_{15}$**	***SD***	**Urea**	***SD***
R_N (%)	32.82	9.71	38.94	5.86	41.60	8.83	46.00	12.74
A_E (kg [grain] kg^{-1} [N])	14.79	5.92	17.40	4.36	17.85	5.00	19.41	6.68
I_P (kg [grain] kg^{-1} [N])	38.33	15.09	45.08	13.85	45.52	14.27	47.09	16.17
2007-08	---------- **Fertiliser type** ----------							
NUE	**Biosolids**	***SD***	**OMF$_{10}$**	***SD***	**OMF$_{15}$**	***SD***	**Urea**	***SD***
R_N (%)	25.57	10.24	55.25	25.59	46.01	11.57	61.04	8.28
A_E (kg [grain] kg^{-1} [N])	18.47	4.21	37.66	22.59	31.23	12.11	37.56	9.00
I_P (kg [grain] kg^{-1} [N])	47.19	18.62	66.38	42.96	59.95	31.96	66.29	28.58
2008-09	---------- **Fertiliser type** ----------							
NUE	**Biosolids**	***SD***	**OMF$_{10}$**	***SD***	**OMF$_{15}$**	***SD***	**Urea**	***SD***
A_E (kg [grain] kg^{-1} [N])	34.61	17.28	35.15	12.00	39.38	9.35	46.71	12.96
I_P (kg [grain] kg^{-1} [N])	78.41	48.31	78.96	43.02	83.19	31.54	90.51	42.92
2009-10	---------- **Fertiliser type** ----------							
NUE	**Biosolids**	***SD***	**OMF$_{10}$**	***SD***	**OMF$_{15}$**	***SD***	**Urea**	***SD***
A_E (kg [grain] kg^{-1} [N])	13.21	2.65	22.91	6.18	25.06	3.38	37.51	9.20
I_P (kg [grain] kg^{-1} [N])	22.45	6.78	32.14	11.35	34.29	9.53	46.75	15.67

With respect to grain yield, and regardless of the nitrogen rate used, it appeared that the ability of the fertiliser to supply nitrogen to the crop at/around the critical period for yield determination (pre-anthesis) was an important factor influencing grain yield. Following the application of OMF, urea-N is first released (mostly within 30 days, as indicated by the results of the incubation studies). The application of OMF at the time corresponding to the standard farm practice for the 1st nitrogen dressing promotes the release of urea-N following application which is used up by the crop early in the season. Subsequently, nitrogen nutrition to the crop needs to be sustained, mostly, by the organic-N fraction in the OMF. A possible explanation is that the mineralisation rate of organic OMF-N is not sufficiently high (or it is not corresponded with crop uptake) and consequently crop yield is affected.

It was argued, for example, that in the 2nd wheat crop in Chippies Field, due to lack of rainfall around the critical period of the crop (pre-anthesis), mineralisation of the organic-N fraction in the OMF was reduced and therefore grain yield declined as nitrogen supply from the fertiliser was limited. This supports the idea of the need to split the nitrogen applications into two dressings and to combine both mineral and organomineral fertilisations as part of the programme. The first nitrogen dressing (mineral nitrogen source) would contribute to promote the early growth of the crop coming out of the winter (by favouring the increase in the number of tillers and leaf area index) and the 2nd dressing could be done with OMF. Nitrogen fertilisation is associated with the increase in the number of tillers and leaf area index (Bavec, et al., 2007). In addition, the increase in crop biomass and leaf are index are associated with the increase in grain yield (Winter and Ohlrogge, 1993; Dalirie et al., 2010). The increment in crop biomass in early stages is required to maximise interception of sunlight and it is related to grain yield (Abbate et al., 1995). It can be argued that because of the content of urea-N in the OMF, the product could potentially be applied in the first dressing, perhaps, by increasing the nitrogen rate in the first split to compensate for the non-mineral nitrogen in the product and subsequently adjusting the nitrogen rate in the 2nd dressing. This is also possible but it may be conditioned by the state of the soils and their trafficability in early spring as, expectedly, larger/heavier equipment may be required for the application of OMF compared with urea or ammonium nitrate.

With regards to rye grass, it was found that for both OMF products, on average, an input of $0.82 * N_{max}$ yielded $0.98 * Y_{max}$ and that this relationship was found to be similar to that of urea ($0.83 * N_{max}$ yielded $0.99 * Y_{max}$). Biosolids required an input of $0.61 * N_{max}$ to yield $0.92 * Y_{max}$ but yield was 22% and 34% lower than the two OMF and urea respectively. When comparing the levels of dry matter yield obtained in the glasshouse and those of the first year in the field (**Tables 9.2** and **9.3** respectively) it can be seen that, overall, these tended to be higher in the plots than the pots. In addition, the optimum dry matter yields, as defined in **Chapter 7** by Y_{10}, were obtained for all fertilisers with nitrogen rates (N_{10}) in the range of *c*.180 to 270 kg [N] ha^{-1} (2009's data) which were lower than the maximum rate used in the glasshouse (300 kg [N] ha^{-1}). In addition, the optimum nitrogen rates obtained in the field were lower than those given for grass in RB209 in most circumstances but Y_{10} was derived from the responses obtained from a single application of nitrogen. Further studies are required to determine grass yield responses for multiple OMF-N applications.

When comparing the data from the glasshouse and the field, a possible explanation for the overall lower nitrogen rates obtained in the plots could be related with differences in temperature conditions in the field and the glasshouse respectively affecting the rate of photosynthesis. Woledge and Dennis (1982) highlighted that the optimum (leaf) temperature of rye grass for maximum rate of net photosynthesis tended to be below 20°C (at 250 W m^{-2} visible radiation) as above this temperature the rate of (dark) respiration increased drastically. Similar observations were made by Jones and Lazenby (1988) who indicated that net photosynthesis increased significantly between 5°C and 25°C (at light saturation). The response to temperature is often difficult as low air humidity reduces photosynthesis through partial stomatal closure (Monson et al., 1982; Jones and Lazenby, 1988). Air temperatures recorded inside the glasshouse (Ghalamboran, 2011; Giné-Bordonaba, 2010; Giné-Bordonaba and Terry, 2010) indicated that the mean temperature between April and July 2009 was 22.5°C (mean temperature's range of 21.0 to 23.0°C) whereas the mean air temperature (Met. Office, 2010) between April and July for the years 2007-09 was 14.1°C (mean temperature's range of 8.9 to 19.0°C). The generally warmer conditions in the glasshouse could have affected crop growth (and yield) at certain periods (radiation also falls outside the main growing period hence photosynthesis also declines despite the warmer indoor temperatures).

It is important to emphasise that in Avenue Field, after four years of continuous OMF application, there were not significant differences in soil extractable-P in OMF-treated plots compared with the controls (unfertilised) plots (mean values of soil extractable-P in 2010 were 66.9, 65.7, and 64.6 mg [P] kg^{-1} for controls, OMF_{10} and OMF_{15}; $LSD_{[5\% \text{ level}]}$ =6.94). Therefore, significant changes in soil-P index could not be detected from the use of OMF. This finding is also supporting the purpose of the formulations and it provided an indication that soil-P levels are, somehow, maintained through the application of OMF despite the low availability of OMF-P. On the other hand, the low N:P ratio of biosolids contributed to raise soil-P levels but the effect was found to be nonsignificant compared to the control for the same LSD value mentioned above (mean value of 71.6 mg [P] kg^{-1} for soil treated with bioslids). In addition, soil extractable-P in the plots treated with urea was reduced compared to that of the controls in 2010 to 63.9 mg [P] kg^{-1}. In Chippies Field, the changes in soil extractable-P were, overall, nonsignificant (p=0.148) overtime with respect to the fertiliser type.

The analyses conducted for soil extractable-K in Avenue Field indicated a significant reduction in soil-K index from 3 (initial level, 211.7 mg [K] kg^{-1}) to 2+ at the end of the experiment.

The largest decrease was observed in urea-treated plots (*c*.152 mg [K] kg^{-1} – mean value over the range of nitrogen rates as recorded in 2010) which also suggested an effect of the fertiliser type on soil-K levels. An effect of the crop was observed following the introduction of the grass in 2009 as the decline in soil-K indexes was recorded at the end of the experiment. The incorporation of straw and the application of OMF-K contributed to sustain soil-K status at approximately pre-existing levels in the two consecutive years of wheat. The relatively larger decrease in soil-K levels observed in urea-treated plots may also be explained by the synergism between the two and its effect on the crop response, as suggested by Milford and Johnston (2007), and by the fact that there was not potash application with the fertiliser

The analyses of selected heavy metals (Cd, Cu, Zn, and Pb) did not show significant changes (p-values >0.05) in their levels compared with those recorded at the start of the experiments in Avenue Field. The values reported were found to be well below the maximum permissible/advisable concentrations indicated in the Revised Soil Code (MAFF, 1998b) given the soil pH values encountered at the experimental site. The application of biosolids, OMF_{10}, OMF_{15} and urea at rates ≤250 kg [N] ha^{-1} should not represent a risk of soil accumulation of these heavy metals when the fertilisers were to be applied under similar soil-crop conditions to those of Avenue Field.

9.6 Economics of OMF application

The results of the regression analyses of fertiliser price suggested that both the price of straight nitrogen and compound NPK will increase by about 15% to 20% between 2010 and 2015 (that is assuming the recent price trend continues). It is understood that this projected increase could provide some room for lower cost fertilisers while encouraging farmers to turn their attention towards organic-based materials. The crop responses obtained in the field experiments were used to provide estimates of the most economic rates of nitrogen application (MERN) from which the corresponding grain yields were calculated (Y_{MERN}). These were used to estimate crop's gross margins (GM); first, by pricing OMF-N ($P_{N\text{-}OMF}$) at the equivalent price of urea-N ($P_{N\text{-}Urea}$) and by assessing the resultant GM of the crop fertilised with OMF against that of urea (**scenario 1**). In this scenario, the GM obtained with OMF were significantly lower compared with urea; i.e. between 190 and 200 £ ha^{-1} for OMF_{10} and between 135 and 140 £ ha^{-1} for OMF_{15}. The differences obtained in the calculated gross margins were mainly due as a result of the overall lower responses obtained in the use of OMF-N compared with urea-N.

In addition, there was an associated increase in the cost of (broadcast) spreading (44.9 to 61.37 £ ha^{-1} for OMF$_{10}$, and 31.2 to 42.9 £ ha^{-1} for OMF$_{15}$) compared with standard mineral fertilisers (14.7 to 20.2 £ ha^{-1}). This led to the conclusion that such price level would be unsustainable and that in order to provide a saleable product there was a need to ensure farmers' margins were not affected by the fertiliser choice. Therefore, a second scenario (**scenario 2**) was suggested which considered reducing the P$_{N\text{-}OMF}$ to a level that allowed matching (±1%) the GM obtained with the use of urea; i.e. GM =999 £ ha^{-1} if employing contractors for spreading operations or 1005 £ ha^{-1} if spreading was done at the farmer's costs. From this scenario, it resulted that the required prices of OMF-N (on average for the harvest years of 2007 to 2010) were £0.05 per kg [N] for OMF$_{10}$ and £0.13 per kg [N] for OMF$_{15}$. This approach required relatively high N-fertilisation levels (302 and 283 kg [N] ha^{-1} – mean MERN values for OMF$_{10}$ and OMF$_{15}$ respectively). It was argued that the use of such high nitrogen rates would discourage the use of OMF if operating within NVZ by exceeding the required field limit of 250 kg [N] ha^{-1}. In order to overcome this problem, a third scenario was presented (**scenario 3**) which considered pricing and applying OMF-N at the price and the MERN of urea-N respectively, and subsidising farmers for the (expected) loss of income. This appeared to be an attractive alternative on the basis of the assumptions made. Firstly, because crop's GM would not be affected as a result of the fertiliser choice; and secondly, because cost savings regarding the disposal/recycling of biosolids would still be possible by United Utilities plc. It was estimated that the financial compensation required for the farmers would be *c*.393 £ ha^{-1} for OMF$_{10}$ and *c*.207 £ ha^{-1} for OMF$_{15}$. Since the cost of agricultural recycling was estimated at 440 £ ha^{-1} (assuming biosolids were applied at their MERN) potential savings of *c*.47 £ ha^{-1} for OMF$_{10}$ and *c*.232 £ ha^{-1} for OMF$_{15}$ would be made which represent potential cost savings of *c*.£1M to £4.4M per year depending on the OMF type.

In addition, and based on the crop responses obtained in Avenue Field for 2006-07, it can be stated that the use of both nitrogen sources, mineral (straight) nitrogen; e.g. urea or ammonium nitrate, and OMF (preferably OMF$_{15}$ in arable situations), as part of the fertilisation strategy would be appropriate to achieve similar levels of grain yield as standard farm practices requiring 100% mineral-N. This statement is based on the results of a single crop season and it would require further investigation. The potential benefits of this approach were discussed earlier (**Section 9.5**) and include; **a.** possible cost-reductions associated with fertilisers (these should not be off-set by the increase in the cost of spreading), **b.** avoidance of soil damage by traffic in likely wetter soil conditions in early spring, and also **c.** gross margins may be increased (assuming cost of spreading remain unchanged and crop yield is unaffected).

The potential drawback for United Utilities plc is that the amount of OMF (hence biosolids) taken up by farmers could be reduced by 40% to 50% (assuming the full N rate was split into applications). Therefore, the land-bank required for recycling could be reduced as a result and compromise recycling targets.

One of the requirements in the development of OMF was the determination of the perceived market value of the products. A methodology was therefore needed to be able to address this requisite. The approach presented (**Chapter 8**) was based on a previous study by Pegurara-Gasparin (2009) who satisfactorily applied the methodology to estimate the willingness to pay for automated agrochemical traceability systems. Therefore, the aim of this work was to provide the basis for future research into the perceived market value of OMF while contributing towards the design of an appropriate pricing strategy for the products.

The implementation of the methodology considered: **a.** the selection of a suitable elicitation method; **b.** guidance for designing of a questionnaire; **c.** defining the required bids amounts; **d.** determining the mean, median, and maximum willingness to pay; **e.** constructing the demand curve for OMF; and **f.** conducting a breakeven analysis. The proposed range of bids was determined based on the results of the gross margin analysis. In addition, it used the regression analyses conducted for the price of nitrogen fertiliser and also a compound NPK fertiliser (20:10:10). These recommended bids were in the range of 0.05 to 0.95 £ kg^{-1} [N] if the study was conducted based on the price of nitrogen, and 25 to 475 £ t^{-1} [NPK] if based on the price of a compound NPK fertiliser such as 20:10:10. The general guidance given for the design of the questionnaire, included the three sections into which it should be divided and the various paths that respondents would follow according to the type of farming activity (arable/grassland) and spreading practice (contractor/own equipment and labour).

This chapter presented a comprehensive overview of the research and discussed the findings encountered while it tried to address the overall aim and objectives formulated in **Chapter 1**. The overall conclusions coming from this research are summarised in **Chapter 10**. These conclusions allowed making a set of recommendations for future work concerning the development of OMF products which are reported in **Chapter 11**.

CHAPTER 10

CONCLUSIONS

10 CONCLUSIONS

This Chapter summarises the overall conclusions coming from this research. These are presented following the aim and objectives of this research as outlined in Chapter 1. The detailed conclusions corresponding to the experimental work conducted can be found in Chapters 3 to 7.

10.1 Conclusions of the chemical and physical properties of OMF

1. Two organomineral fertilisers products (OMF) have been suggested: OMF_{10} and OMF_{15} which have the following $N:P_2O_5:K_2O$ compositions: **10:4:4** and **15:4:4** respectively (approximately). These two formulations were suggested for use in grassland and as well as arable cropping. The 10:4:4 was formulated and fits situations where there is a lower soil-P index.
2. The chemical composition of the materials varied between the years; the nitrogen concentration in the products was in the range of 9.83% to 16.05% for OMF_{15} and 7.15% to 10.52% for OMF_{10}.
3. The physical properties of the materials also varied widely between years, particularly, with regards to the particle size and size distribution. The measured physical properties of OMF were:
    a. Particle size and size distribution (mean values for 2007 to 2010’s samples)
        - OMF_{10}: D_{50} =4.45 mm; D_{16} =2.39 mm; D_{84} =6.91 mm.
        - OMF_{15}: D_{50} =4.60 mm; D_{16} =2.52 mm; D_{84} =7.16 mm.
    b. Particles were in the range of <0.60 mm (up to 3% and 6% for OMF_{10} and OMF_{15} respectively) to 37.0 mm (up to 5.24% and 2% for OMF_{10} and OMF_{15} respectively).
    c. Particle density (mean values based on 2010’s samples)
        - OMF_{10}: 1296.8 kg m^{-3} (range 904.2 to 2239.9 kg m^{-3}).
        - OMF_{15}: 1357.0 kg m^{-3} (range 713.1 to 1638.2 kg m^{-3}).
    d. Bulk density (mean values for 2007 to 2010’s samples)
        - OMF_{10}: 622.7 kg m^{-3} (range 550.2 to 742.1 kg m^{-3}).
        - OMF_{15}: 603.1 kg m^{-3} (range 549.4 to 705.4 kg m^{-3}).
    e. The measurement of the compression strength of individual particles (based on 2008’s samples) demonstrated that OMF particles tended to deform under pressure and behaved in a plastic way. OMF particles did not show a characteristic breaking force that induced the fracture of the particle.

    This was attributable to the organic nature of the material and their moisture content (range of 15% to 17%). This can affect the aerodynamic properties of the particles hence their landing distance. A possible way to mitigate it would be by maintaining the moisture content of the material to a minimum (e.g. $\leq$10%) but the decision should ultimately be made considering possible cost increases associated with the energy required for drying the material. Particle's deformation started below 15 *N* which was the reference (lower) limit suggested in earlier studies for urea particles to prevent fracture. For urea, the forces required to induce the fracture of the particles were between 23 *N* and 32 *N* depending on the particles' diameter.

    f. The chemical and physical quality of the materials affected the overall performance of the crops compared with urea and provided a source of variability to the results reported.

4. A theoretical model for fertiliser particle distribution studies was developed. It showed that it may be possible to apply OMF_{10} and OMF_{15} at 12 m to 18 m tramline spacing (final to be confirmed when practical distribution patterns are known). The tables of particle diameter against particle density produced with the model, and based on earlier studies, can be used to determine the basic characteristics for OMF that are required to achieve a particular spreading width. The model requires validation against data obtained experimentally.

10.2 Conclusions of the study of nutrients availability of OMF

The **incubation studies** were conducted to determine the availability of nitrogen and phosphorus following soil application of OMF_{15} under controlled conditions of temperature and soil moisture content. The findings coming from these studies are summarised below.

1. The assessment of the **nitrogen availability** of OMF_{15}, indicated that:
    a. The greatest rate of nitrogen release from OMF_{15}, as percentage of the total-N applied, occurred in the first 30 days following soil application. It ranged between 59% (*c*.88 kg [N] ha^{-1}) and 72% (*c*.216 kg [N] ha^{-1}) in the sandy loam, and between 40% (*c*.60 kg [N] ha^{-1}) and 57% (*c*.171 kg [N] ha^{-1}) in the clay loam soil depending on the nitrogen application rate.
    b. Subsequently, the percentage nitrogen available (relative to the total applied) increased up to 10% in the sandy loam soil and between 23% and 28% in the clay loam soil.

   c. The greatest rate of nitrogen release from urea, as percentage of the total-N applied, also occurred in the first 30 days following soil application. It ranged between 96% (*c*.144 kg [N] ha^{-1}) and 99% (*c*.297 kg [N] ha^{-1}) in the sandy loam and between 82% (*c*.123 kg [N] ha^{-1}) and 99% (*c*.297 kg [N] ha^{-1}) in the clay loam soil depending on the nitrogen application rate. Thereafter, SMN remained relatively constant in most circumstances. Overall, SMN was significantly higher in urea- compared with OMF_{15}-treated soil.
   d. An accumulated thermal time of 2250 dºC was needed for OMF_{15} to release between 68% and 70%, and between 68% and 79% of the total-N applied in the sandy loam and the clay loam soils respectively depending on the nitrogen application rate. This accumulated thermal time is likely to be reached in early August in-field conditions which suggested that mineralisation of the organic-N fraction in the OMF would progress after the harvest of winter cereal crops.
   e. Based on the above, it is expected that up to 20% of the nitrogen applied with OMF would be carried over onto the following autumn-sown crop for which residual OMF-N should be accounted for if N-fertilisation in the seedbed was required.
2. The assessment of the **phosphorus availability** of OMF_{15}, indicated that:
   a. Phosphorus availability from OMF_{15}, as percentage of the total-P applied, was low throughout the experiment. It ranged from -4.1% (*c*.6.2 kg [P_2O_5] ha^{-1}) to 6.4% (*c*.9.5 kg [P_2O_5] ha^{-1}) in the sandy loam and from -5.6% (*c*.8.4 kg [P_2O_5] ha^{-1}) to 4.6% (*c*.13.5 kg [P_2O_5] ha^{-1}) in the clay loam soil. The negative values recorded indicated that P-availability was reduced in the treated soils compared with the control. The low availability of OMF-P can be attributable to the technique used for the removal of phosphorus during the wastewater treatment.
   b. Despite the generally low availability of applied OMF-P, a change in soil-P index from 5 to 6 was observed but the overall increase in soil extractable-P was marginal and it remained close to the initial levels recorded in both soils.
   c. For single superphosphate (SSP), P-availability (as percentage of the total-P applied) was significantly higher than that of OMF_{15}-P. It ranged from 37% to 46% in the sandy loam, and from 16% to 26% in the clay loam soil. The application of SSP induced a significant increase in soil extractable-P levels compared with the untreated soils.

As a result, soil-P index changed from 5 to 6 in both soil types. This was expected given its high solubility (92%-94% water soluble-P).

10.3 Conclusions of the agronomic characteristics of OMF

The agronomic characteristics and the fertiliser potential of OMF products were investigated at two different experimental scales which included pots (**glasshouse studies**) and plots (**field studies**). The findings coming from these studies are summarised below.

10.3.1 Crop yield and responses

1. The studies conducted in the **glasshouse** indicated that:
    a. The response functions showed linear increments in dry matter yield for the range of nitrogen application rates investigated (0 to 300 kg [N] ha^{-1}) for all treatments.
    b. The increments in dry matter yield in OMF-treated pots ranged from 14.2 to 19.7 kg [DM] per kg of additional N (2007) and between 7.7 and 10.5 kg [DM] per kg of additional N (2008 and 2009). For urea, these were *c*.25 kg [DM] per kg of additional N (2007) and between 6.5 and 11.3 kg [DM] per kg of additional N (2008 and 2009) whereas for biosolids the increments were lower overall but more consistent between-years (range of 7 to 12 kg [DM] per kg of additional N).
    c. Similarly, dry matter yield in OMF_{10}-, OMF_{15}- and urea-treated pots tended to match that of biosolids overtime under warm (*c*.22.5°C) glasshouse conditions. In 2007, mean dry matter yields with OMF_{10}, OMF_{15}, and urea, relative to biosolids, were 13.5%, 27.4%, and 55% higher respectively. Mean dry matter yield obtained with biosolids was 5613 kg [DM] ha^{-1}.
    d. In 2008 and 2009, dry matter yields relative to biosolids, were 8.1% and 1.6% (OMF_{10}), 7.9% and 5.9% (OMF_{15}), and 16.8% and 3.3% (urea) respectively. Mean dry matter yields for biosolids were 5637 and 5178 kg [DM] ha^{-1} for 2008 and 2009 respectively. These differences were significant in 2007 and 2008 but they were not in 2009.
    e. The reduction in the overall performance of OMF_{10}, OMF_{15} and urea overtime could be related to the surface-application of the fertilisers, possible losses of nitrogen by volatilisation from the fertiliser fraction carrying urea, and the relatively late timing of fertiliser application in 2008 and 2009 in relation to the maximum growth period of grass.

In the pots treated with biosolids dry matter yield was sustained (range of 5000 to 6000 kg [DM] ha^{-1} on average) possibly as a result of enhanced N-mineralisation and N-uptake by the crop given the experimental conditions in the glasshouse. The pots treated with urea followed the same trend as OMF but the decrease in dry matter yield in years two and three was greater compared with 2007's levels.

f. Apparent nitrogen recovery (R_N) varied between-years but it tended to decrease overtime which was consistent with the overall decline in dry matter yield reported above. R_N was related to the concentration of readily available nitrogen in the fertilisers. The following values of R_N were encountered:
    - Biosolids: 23.3% to 37.4% (2007), and 14.9% to 26.2% (2008).
    - OMF_{10}: 38.2% to 43.8% (2007), and 21.2% to 35.7% (2008).
    - OMF_{15}: 46.7% to 53.2% (2007), and 21.4% to 30.2% (2008).
    - Urea: 67.3% to 86.1% (2007), and 23.7% to 39.9% (2008).

g. Apparent nitrogen recovery was marginally larger in the sandy loam compared with the clay loam soil (*c*. +9%); the differences encountered between the two soils were significant. This effect was possibly due to the lower clay content in the sandy loam and its overall lower fertility status compared with the clay loam.

h. In general, the agronomic efficiency index (A_E) showed a similar trend to that indicated for apparent recovery. It was initially higher for urea and OMF than biosolids, but it decreased overtime and tended to match that of biosolids.

2. The studies conducted in the **field** (College Farm, Silsoe) indicated that:
    a. For both winter wheat and rye grass, the relationships between crop yield and nitrogen application rate were explained by quadratic functions. The R^2 values showed acceptable fits of the quadratic models ($R^2 \geq 0.60$). In general, crop yield was enhanced with the concentration of (available) nitrogen in the fertiliser. The use of urea outperformed OMF_{15}, OMF_{10} and biosolids with regard to crop yield (in both crops) and crop yield components (in winter wheat).

    b. For **wheat**, the quadratic functions fitted to the data allowed deriving the MERN and Y_{MERN} which were required to conduct the economic analyses.

    c. The relative yield increases, relative to biosolids were 11.5% (OMF_{10}), 23% (OMF_{15}), and 42% (urea), on average over the four crop seasons and for the entire range of nitrogen rates used.

The mean grain yield obtained with biosolids was 7009 kg ha^{-1}, also on average over the four crop seasons and for the entire range of nitrogen rates used.

d. In 2006-07, grain yield from OMF$_{10}$ and OMF$_{15}$-treated plots benefited from the application of UAN (33% N – solution at 100 kg [N] ha^{-1}) in the first dressing and there were not significant differences in yield compared with urea (all treatments yield *c*.10500 kg ha^{-1}).

e. From the above, there appears to be an advantage in splitting the total nitrogen rate into two dressings. The application of nitrogen may be approximately 40% to 50% of the full rate in the first dressing (typically late February to March), using a straight nitrogen source, and the remaining 50% to 60% in the second dressing, approximately 30 to 40 days later. This application strategy requires further investigation as it is based on the results obtained from a single crop season (2006-07).

f. The apparent nitrogen recovery (R_N) in the wheat crop (on average over the range of nitrogen rates) following application of OMF and urea ranged between 39% and 46% in 2006-07, and between 46% and 61% in 2007-08 respectively. For biosolids, R_N ranged between 25% and 32% both years which demonstrated that R_N was related to the concentration of (available) nitrogen in the fertiliser.

g. For **grass**, the terms Y_{10} (optimum yield) and N_{10} (nitrogen rate required for Y_{10}) were derived from the quadratic response curves fitted to the data. These were (2009's data – 3 cuts):
  - OMF$_{10}$: Y_{10} =12255 kg [DM] ha^{-1}; N_{10} =180 kg [N] ha^{-1}.
  - OMF$_{15}$: Y_{10} =13574 kg [DM] ha^{-1}; N_{10} =210 kg [N] ha^{-1}.
  - The calculated optimum nitrogen rates for OMF$_{10}$ and OMF$_{15}$ represented a reduction in the total nitrogen input of *c*.60-90 kg [N] ha^{-1} compared with biosolids for an increase in dry matter yield of *c*.2000-3000 kg [DM] ha^{-1} on average for the two seasons.

h. The increase in dry matter yields, relative to biosolids, was: 22% (OMF$_{10}$), 33% (OMF$_{15}$), and 34% (urea) on average for 2009 and 2010 and over the entire range of nitrogen rates used. The mean dry matter yield for biosolids was 9285 and 5394 kg [DM] ha^{-1} for 2009 (three cuts) and 2010 (two cuts) respectively.

- i. For both OMF products, on average, an input of $0.82*N_{max}$ yielded $0.98*Y_{max}$ and similarly for urea ($0.83*N_{max}$ yielded $0.99*Y_{max}$); whereas biosolids, required an input of $0.61*N_{max}$ to yield $0.92*Y_{max}$ but yield was between 22% and 34% lower than OMFs and urea respectively.
- j. The timing of application and nitrogen rates in each split should be adjusted to the characteristics/requirements of the production system. However, the general recommendations given in RB209 (MAFF, 2000) should be followed when using OMF. These appear to be compatible with the characteristics of the products.
- k. Overall, the optimum nitrogen rates encountered for grass with the application of OMF were lower than those given in RB209 (e.g. grazing beef/dairy cows which require up to 380 kg [N] ha^{-1} per year) but responses were obtained for a single application of nitrogen. Hence, these should be determined for splits according to the approximate timings of application shown in RB209 and in relation to the particular grass-production system.

10.3.2 Soil chemical properties

1. The analyses of **soil extractable-P** in Avenue and Chippies Fields indicated that, on average, the use of OMF_{10} and OMF_{15} did not change soil-P levels significantly compared with the unfertilised controls.
    - a. In Avenue Field, the use of biosolids and urea significantly increased and decreased, respectively, soil extractable-P levels compared with the untreated control soils.
    - b. In Chippies Field, the changes in soil-P levels were not significant as a result of the fertiliser type but there was an indication that biosolids tended to increase soil extractable-P.
2. Based on the above, soil-P index in OMF-treated soils remained close to constant (soil-P index 5) over the range of application rates investigated. This finding is therefore supporting the reasons for the initial formulations. Therefore, the use of OMF should not contribute to soil-P enrichment if the fertilisers were to be applied in similar soil-crop conditions to those described in this work. The changes recorded as a result of the use of urea and biosolids did not induce changes in soil-P index in Avenue and Chippies Fields but they should be monitored in the longer term given the trends observed.

3. In the glasshouse studies, soil-P index in OMF-treated pots did not change compared with the initial levels (index 5) whereas the use of biosolids induced a change in soil-P index from 5 to 6. In urea-treated pots, although the index did not change overtime, there was a significant decrease in soil extractable-P from 99.1 mg [P] kg^{-1} (initial level) to 93.2 mg [P] kg^{-1} (end experiment) thereby being consistent with the trends reported for the soils in the field.
4. $\mathbf{TN_{soil}}$ was significantly increased as a result of the fertilisers' application in both Avenue and Chippies Fields.
    1. In Avenue Field, there was an effect of the crop as TN_{soil} increased significantly in the control plots after the introduction of grass in 2009 (from 0.147% in post-harvest 2008 to 0.164% w w^{-1} at the end of the experiment). In OMF-treated plots TN_{soil} increased significantly compared with the initial levels (from 0.149% to *c*.0.163% w w^{-1} in 2010) but not significant differences were found between OMF-treated plots and the controls in 2010 and the same was observed for urea although TN_{soil} increased comparatively to a lesser extent (0.158% w w^{-1} in 2010). The use of biosolids significantly increased TN_{soil} (from 0.149% - initial, to 0.170% w w^{-1} in 2010).
    2. In addition, in Avenue Field there was a positive correlation between the increase in TN_{soil} and the nitrogen application rate.
    3. In Chippies Field, there were not significant differences in TN_{soil} with respect to the fertiliser type; all treatments showed approximately the same levels of TN_{soil} (*c*.0.147% w w^{-1}) in post-harvest of wheat 2010.
5. The analyses of **SMN** indicated that:
    1. In general, SMN levels were, on average, significantly larger in post-harvest of wheat compared with the values recorded prior to the fertiliser application in the spring (<4.3 and <5.4 mg [N] kg^{-1} for Avenue and Chippies Fields respectively). SMN levels in post-harvest of wheat varied between 4.28 mg [N] kg^{-1} (Avenue Field) and 16.9 mg [N] kg^{-1} (Chippies Field) on average over the entire range of nitrogen rates and fertiliser types used in both sites. These results suggested possible losses of residual nitrogen over the winter time.
    2. In Avenue Field, SMN levels from OMF-treated plots in post-harvest of wheat (2008) were: *c*.4.4 mg [N] kg^{-1} equivalent to *c*.11.8 kg [N] ha^{-1} assuming a depth of 0.2 m.

   c. In Chippies Field, SMN levels from the same treatments as above in post harvest of wheat were: *c*.6.5 mg [N] kg^{-1} equivalent to *c*.17.4 kg [N] ha^{-1} for the same depth of soil as above.
   d. The values of SMN recorded in Avenue Field during the grass years were consistently lower (range of 0.8 to 2.5 mg [N] kg^{-1}) than those during the wheat years possibly as a result of the rate of nitrogen uptake by the grass in relation to the timing of sampling.
6. The analyses of **soil extractable-K** conducted in Avenue Field showed an effect of the crop and also the fertiliser type on soil-K status. Soil-K levels in post-harvest of the 2nd wheat (2008) were approximately close to the initial level (211 mg [K] kg^{-1}). However, after 2 years of grass, K-index decreased from 3 to 2+.
7. The extent to which soil extractable-K decreased was related to the nitrogen concentration in the fertiliser. The largest decrease was observed in urea-treated plots (range 149 to 155 mg [K] kg^{-1}). The plots treated with OMF showed intermediate soil-K levels (range 150 to 175 mg [K] kg^{-1}) between biosolids and urea. This was possibly due to the interaction between nitrogen and potassium in their relative uptakes by the crop, given the pre-existing satisfactory soil-K level and the availability of nitrogen in the fertiliser.
8. The analyses of **SOM** in the glasshouse studies showed that there was an overall increase of *c*.18% compared with the initial levels (from 4.38% to 5.19% respectively). The largest increase compared with the controls was observed in biosolids-treated pots (*c*.7%) followed by OMF and urea where it increased between 4.75% and 2.3% respectively. There was an effect of the crop since the control soils also raised SOM compared with their initial levels, especially, in the sandy loam soil (by *c*.10%).
9. The analyses of **SOM** indicated that:
   a. For the field studies SOM did not show significant differences between the control and the treatments. However, in Avenue Field, there was an overall increase in SOM compared to the initial levels (from 3.88% to 4.25%). This could be attributable to the introduction of the grass in 2009 as the effect could not be observed in Chippies Field when the soil was under arable rotation.
   b. In both fields there appeared to be an indication that the use of biosolids would contribute to increase SOM levels as SOM in biosolids-treated plots increased to a larger extent than the other treatments (from 3.87% to 4.36%, and from 3.42% to 3.51% in Avenue and Chippies Fields respectively).

This was not significant compared with the other treatments but it could be an indication of a trend for the longer term.

10. The use of OMF did not induce significant changes in **soil pH** when compared with the unfertilised control soils; this was true for both the glasshouse and the field studies. However, in the pots there was an overall increase in soil pH possibly associated with the quality of the water used for irrigation.
11. The analyses of **heavy metals** in soil (Cd, Cu, Zn, and Pb) did not show significant changes in their levels compared with those recorded at the start of the experiment in Avenue Field. It was found that:
    a. The values encountered were well below the maximum permissible/advisable concentrations.
    b. From the above, the application of OMF_{10} and OMF_{15} should not represent a risk of soil accumulation of these heavy metals when the fertilisers were to be applied under similar soil-crop conditions to those of Avenue Field.

10.4 Conclusions of the economic analyses

1. Based on the yield to nitrogen response curves, the most economic rates of nitrogen application (MERN) and their corresponding grain yields (Y_{MERN}) were calculated assuming the price of OMF_{10}- and OMF_{15}-N was equivalent to the price of urea-N. This was on average 0.65 £ kg^{-1} (range 0.42 to 1.04 £ kg^{-1}).
2. The calculated **MERN** and $\mathbf{Y_{MERN}}$ on average over the four harvest seasons were:
    a. $\mathbf{OMF_{10}}$: 257 kg [N] ha^{-1} (range 166 to 367 kg [N] ha^{-1}); Y_{MERN} =9095 kg ha^{-1} (range 7083 to 10707 kg ha^{-1}).
    b. $\mathbf{OMF_{15}}$: 248 kg [N] ha^{-1} (range 190 to 342 kg [N] ha^{-1}); Y_{MERN} =9487 kg ha^{-1} (range 7222 to 12372 kg ha^{-1}).
    c. **Urea**: 225 kg [N] ha^{-1} (range 197 to 256 kg [N] ha^{-1}); Y_{MERN} =10347 kg ha^{-1} (range 7947 to 12925 kg ha^{-1}).
    d. The use of OMF_{10} and OMF_{15} at the MERN indicated above represent an improvement in grain yield of *c.*1100-1500 kg ha^{-1} compared with biosolids for a similar nitrogen application rate (±10 kg [N] ha^{-1}) on average over the four harvest seasons investigated.
3. Based on the MERN and Y_{MERN} values reported above, and on average for the four harvest seasons, it resulted that:

   a. Gross margin from the use of OMF_{10} was between 798 and 815 £ ha^{-1};
   b. Gross margin from the use of OMF_{15} was between 859 and 871 £ ha^{-1};
   c. The gross margin from the use of urea was *c*.1000 £ ha^{-1}.

4. In order to match ±1% of the gross margin of urea with the use of OMF, the prices of OMF-N were estimated at *c*.0.05 £ kg^{-1} N (range of 0.0 to 0.11 £ kg^{-1} N) for OMF_{10} and *c*.0.13 £ kg^{-1} (range of 0.12 to 0.21 £ kg^{-1} N) for OMF_{15} on average for the four harvest seasons.
5. The reduction in the price of OMF-N required to match the gross margin of urea does not appear to be a viable solution since the required nitrogen application rate with OMF-N is inevitably increased, on average, above the field limit of 250 kg [N] ha^{-1}.
6. Due to the price of urea for coating OMF granules, the relatively low release period of organic-N, and the relative shapes of the yield to nitrogen response curves for OMF and urea, it is unlikely that OMF can be competitively priced. Hence, the cost to the farmer must be such that gross margins are maintained and consequently the product needs to be subsidised by United Utilities plc. Given the assumptions made in the scenario it would be still an economic proposition for United Utilities plc to do this when compared to the current costs of recycling.
7. From the above, there appears to be potential for the further development of the OMF product, especially, in the improving granulation and coating.

10.5 Perceived market value of OMF

1. A methodological approach to determining the perceived market value of OMF was presented. The methodology follows the studies conducted by Pegurara-Gasparin (2009) which were based on the use of contingent valuation techniques. The proposed approach aims at:
   a. Providing a platform for future research into the willingness to pay for OMF products, and
   b. Contributing towards the design of an appropriate pricing strategy for the products.

CHAPTER 11

PRACTICAL RECOMMENDATIONS

11 PRACTICAL RECOMMENDATIONS

1. The application of nitrogen at the rate indicated by the MERN is crucial to maximising the economic result. The MERN values corresponding to OMF_{10} and OMF_{15} were, on average, relatively higher than those reported in RB209 in most circumstances. The MERN depends on the shape of the response curve and also on the relative prices of nitrogen and grain. The effect of a reduction in the price of nitrogen, for a fixed price of the grain, results in increased MERN. It is expected that improvements in the physical and chemical characteristics of the product will enhance the response of the crop to applied OMF-N. Hence, the MERN, for a given price ratio, may be reduced.

2. Therefore, there is a need to improve the quality control for physical and chemical properties of OMF. In this respect, it is suggested that initial efforts should be made to perfect OMF_{15} as this product has higher nitrogen content and it could better fit the needs of the market in the North West region given the relatively high P-indexes in the main area of United Utilities plc for the recycling of biosolids. This focus on quality control, needed for fertiliser selling, will require a cultural shift within waste management companies.

3. It is also necessary to produce sufficient quantities of OMF of the right quality to conduct spreading tests based on standard tests procedures. From this, it will be possible to devise the application strategy that may enable OMF application for 18 or 24 m wide tramlines. In order to satisfy this requirement, a higher range (%) of particle diameters may be needed which could be pre-assessed by applying the particle trajectory model developed in this research. The particle trajectory model requires validation either using OMF or published experimental data. In increasing the range of particle diameters, there is a potential drawback which could arise from increased manufacturing costs associated with the granulation.

4. Improvements in the physical and chemical characteristics of OMF are a requirement for both economic and environmental reasons. Economically as they have a direct effect upon crop performance and consequently profit margins. Environmentally as uneven spreading of fertilisers can increase the risk of pollution through poor fertiliser use efficiency by the crop.

5. It is important to consider in more detail the logistics of applying a straight nitrogen source in the first fertiliser dressing. The second nitrogen dressing may be conducted using OMF which would provide the remaining amount of nitrogen required to achieve the MERN. The application of nitrogen should be done in accordance with the timings and nitrogen rates given in RB209.

6. The application of nitrogen to winter wheat may be approximately 40% to 50% of the full rate in the first dressing (typically late February to middle of March), using a straight nitrogen source, and the remaining 50% to 60% in the second dressing with OMF, approximately 30 to 40 days later. However, it is recommended that further studies are conducted to determine the optimum timing for OMF application when combined with straight nitrogen sources as part of the fertilisation strategy. It is envisaged that these studies will benefit from the findings reported from the pilot experiments conducted in Avenue Field in 2006-2007.

7. There is a need to perform further, more detailed, economic analysis when the actual costs of production of OMF are known. In addition, it is necessary to conduct a willingness to pay study based upon the recommendations given following the work of Pegurara-Gasparin (2009).

8. The two years of data collected in the lysimeters studies concerning N_2O emissions and nitrogen and phosphorus leaching following application of OMF and urea to winter wheat and rye grass needs analysis and reporting by the author.

CHAPTER 12

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12 REFERENCES

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APPENDICES

APPENDIX CHAPTER 1

Appendix A.1.1: Brief description of the coating process of OMF and pilot granulator

Urea Coating for OMF formulation

Development of Urea Melter

Document facilitated by: **Sidath Gedara**, KTP Associate, United Utilities plc, Ellesmere Port Wastewater Treatment Plant, Little Stanney, Chester, CH2 4HZ. Email: sidath.gedara@uuplc.co.uk (22 July 2009).

Introduction

The coating process supplements mineral nutrients to sludge granules in required quantities to formulate OMF. Production of OMF with bench scale nutrient coating practices has previously been successful, however, scaling-up the process to produce significant quantities (over 100kgs) of OMF was been a challenge. The OMF project has identified the importance of developing the mechanism to melt urea efficiently and to spray them to form even coating. This document summaries the previous project experiences and literature reviews towards the development of Urea coating process.

Process requirements

The “ideal coating” process should,

- be capable of producing a uniform coating around the sludge granules to distribute mineral nutrient evenly through the batch produced,
- have minimum impact of sludge granules & minimise the production of dust during formulation – possibly by crushing sludge granules,
- transfer Urea melt to sludge granules effectively without making unbound solidified urea dust,
- make sure that the Urea coating and potash dust are hardbound to the surface of sludge granules in order to withstand any physical impacts on spreading OMF products,
- not form any clogs of Urea or clogs of Urea & sludge granules.

Proposed process description

The proposed OMF coating process is a batch process (even at the required scale). In the initial stage of the process, Urea granules are melted in the presence of steam using the Urea-melter, followed by spraying the melt on sludge granules to form the coating (this follows the technology use to produce urea granules which can be found at the following link: http://nzic.org.nz/ChemProcesses/production/1A.pdf

The sludge granules are mixed using a rotary drum mixer (e.g. cement mixer) while spraying the urea melt, to have an even coating around the granules. Ground potash (possibly mix with Urea formaldehyde to improve the binding – further research required) is added simultaneously in small quantities. Following this Urea spraying further air drying may be required to dry-off the coating & any fine dust can be screened out.

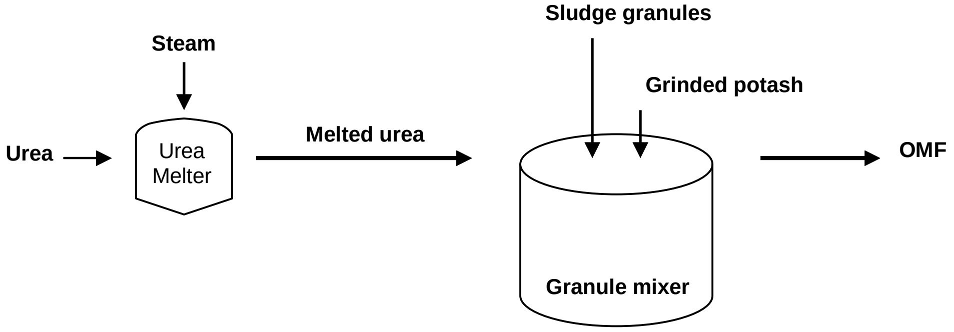

Figure 1: Simplified overview of the coating process.

Process equipment:

Coating process demands for 2 major equipments as follows,

- Urea melter – use to melt, store and spray urea on sludge granules. Comprise with heat insulated melting container, steam generator, air compressor & spraying Nuzzle
- Granule mixer – use to mix granules while spraying the hot Urea melt to form even coating

Material inputs:

- Urea – fertiliser urea (46% N) in granular form
- Potash – fertiliser potash (60% P_2O_5)
- Steam – (95 - 100^0C)
- Granulated sludge – (~90% DS, 3-6mm granules)

The scale:

Each batch would take sludge granules up to the amount that can conveniently mix using the selected mixer – 40 kg maximum. Table 1 shows the different amount of materials required for given formulations for each batch.

Table 1: Material requirement for the different OMF formulations.

Formulation	Base granules (kg, 90% DS)	Urea (kg, 46% N)	Potash (kg, 60% P_2O_5)	Total formulation (kg)
10:4:4	32	5.6	2.4	40
15:4:4	27.6	10	2.4	40

The Urea melter should be capable of melting over 10 kg of urea in each batch.

Learning points

Urea melting:

- Melting point of the Urea is 132.7^{0}C and Urea starts to decompose at 135^{0}C. As such, Urea melting should be conducted in the presence of steam and the working temperature of the Urea melter should not exceed 130^{0}C. http://www.agrium.com/uploads/Urea_Industrial_Grade_Granular_MSDS14055.pdf

- The amount of steam use to melt urea in the process is important. It is better to use lesser steam as possible as far as the dry solids content of the final product is concern; however, previous experiences suggest making a clear melt (without any solid urea) would helps to form an even coating.

- Based on the previous urea melting trials, a vigorous mixing process may be required while supplying steam for Urea melting. Mixing would distribute the energy/ steam throughout the urea batch and would make the process efficient.

- It is crucial to cut down the heat losses from all parts of the Urea melter. Trace heating mechanism/ cables would help to keep the temperature of the melter above 100^{0}C all the time, especially the pipelines which transfer urea melt to the nozzles for spray.

- Use of pressurised system (similar to steam cooker/ Autoclave technology) could increase the efficiency of Urea melting and result a melt with high temperature (e.g.: 120^{0}C or above). Further, high pressure would possibly help to spray the melt on the granules. However, possibility of creating adequate steam pressure without exceeding the required working temperature (less than 130^{0}C) needs to be further investigated. Table 2 show the steam temperature at different pressures. Health and safety associated with such pressurised system would also be a concern.

Table 2: Steam temperature at high pressure.

Pressure		Temperature
(kPa, kN m^{-2})	**bar**	**^{0}C**
95	0.95	98.2
100	1.00	99.6
101	1.01	100.0
110	1.10	102.3
130	1.30	107.1
150	1.50	111.4
170	1.70	115.2
190	1.90	118.6
220	2.20	123.3
260	2.60	128.7
280	2.80	131.2
320	3.20	135.8

(Source: http://www.engineeringtoolbox.com/saturated-steam-properties-d_101.html)

Urea spraying

- As experienced before, urea melt releases its energy fast and tend to get solidified rapidly (when the melt is at 100^{0}C). This could be a possible threat when spraying urea melt, as fine droplets can solidify before touching the sludge granules making unbounded urea dust. Other than the fineness of the spray, following parameters may also decide how fast the melt get solidified which needs further investigation:

  - amount of steam/ water used to melt urea,
  - temperature of the urea melt,
  - distance/ time that urea droplets needs to travel before hit the sludge granules,
  - air temperature.

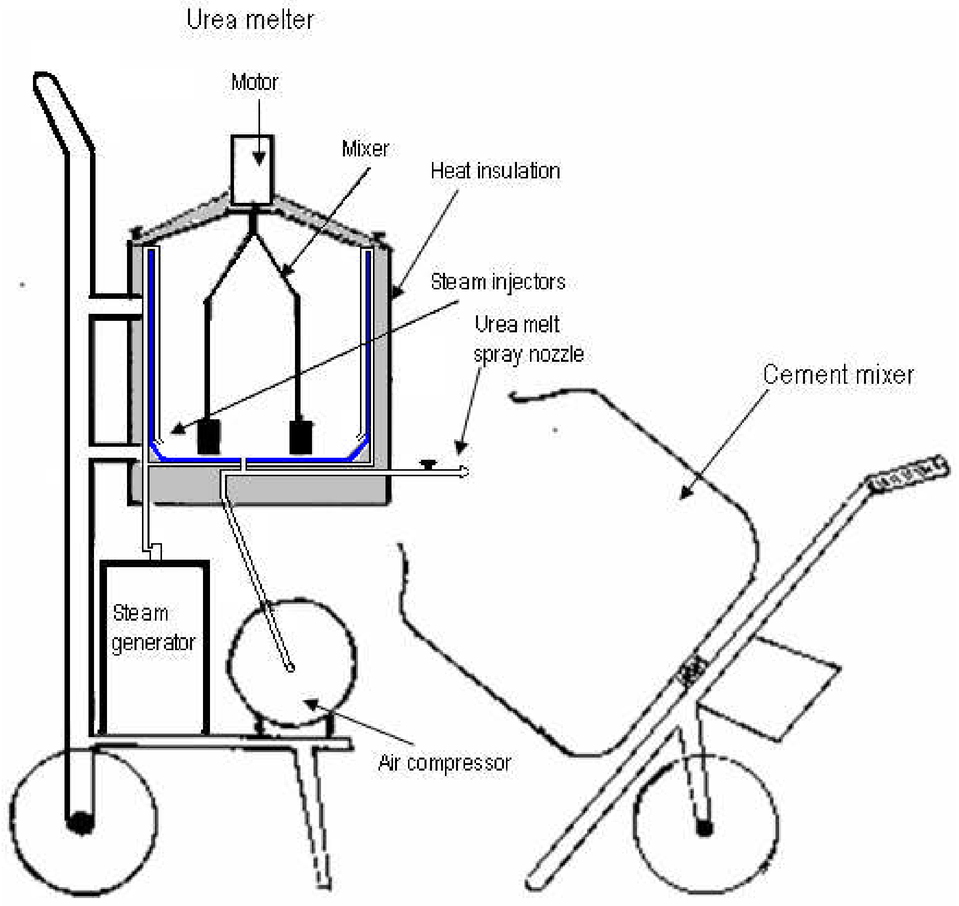

Figure 2: A diagram showing the proposed design.

Pilot granulator

(Property of United Utilities plc)

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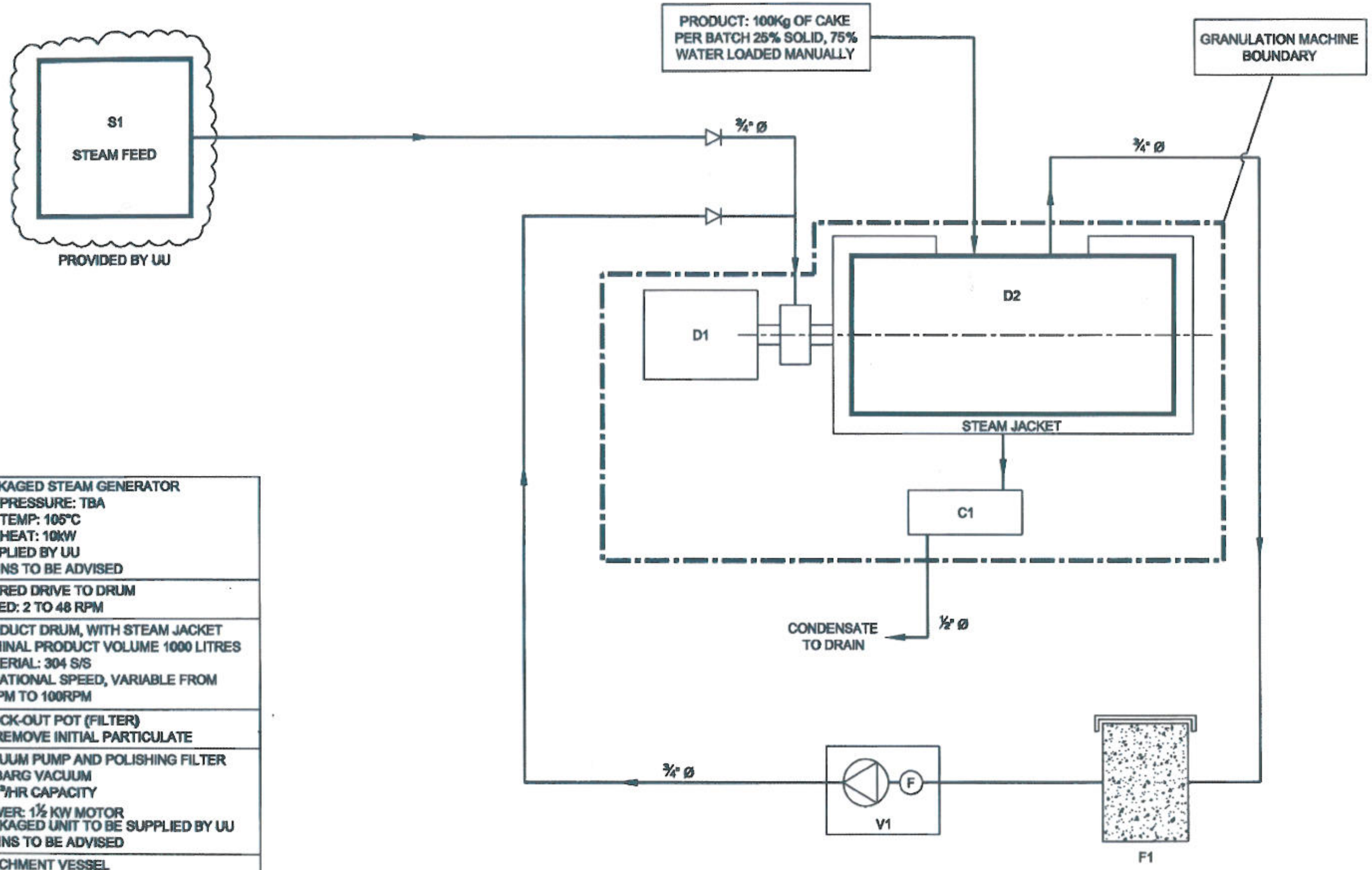

S1	- PACKAGED STEAM GENERATOR PRESSURE: TBA TEMP: 105°C HEAT: 10kW - SUPPLIED BY UU - CONNS TO BE ADVISED
D1	- GEARED DRIVE TO DRUM - SPEED: 2 TO 48 RPM
D2	- PRODUCT DRUM, WITH STEAM JACKET - NOMINAL PRODUCT VOLUME 1000 LITRES - MATERIAL: 304 S/S - ROTATIONAL SPEED, VARIABLE FROM 20RPM TO 100RPM
F1	- KNOCK-OUT POT (FILTER) - TO REMOVE INITIAL PARTICULATE
V1	- VACUUM PUMP AND POLISHING FILTER - 0.7 BARG VACUUM - 40M³/HR CAPACITY - POWER: 1½ KW MOTOR - PACKAGED UNIT TO BE SUPPLIED BY UU - CONNS TO BE ADVISED
C1	- CATCHMENT VESSEL - NOMINAL CAPACITY: 0.6M³ - MATERIAL: 304 S/S

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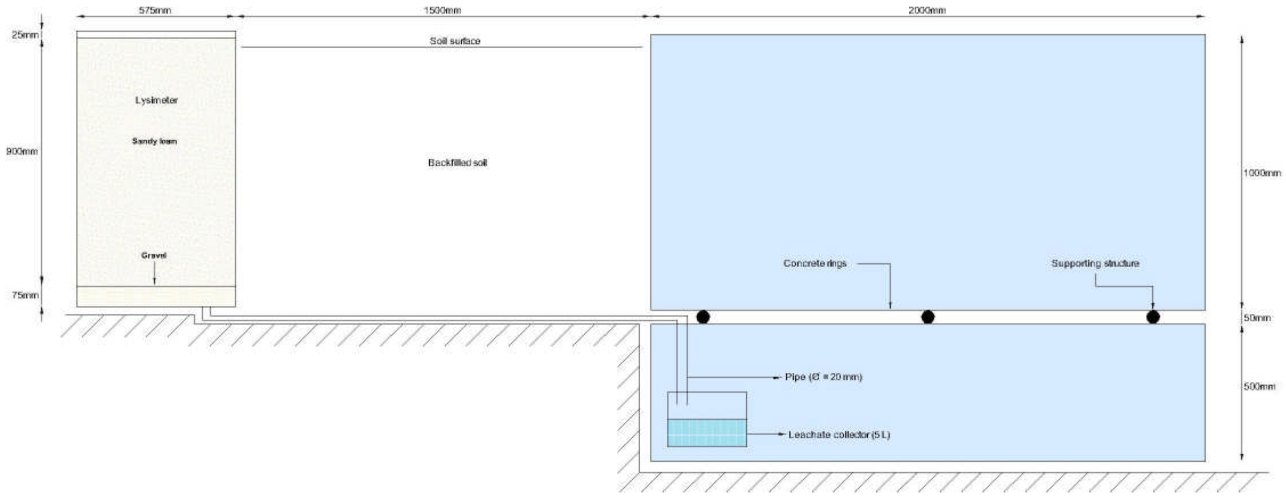
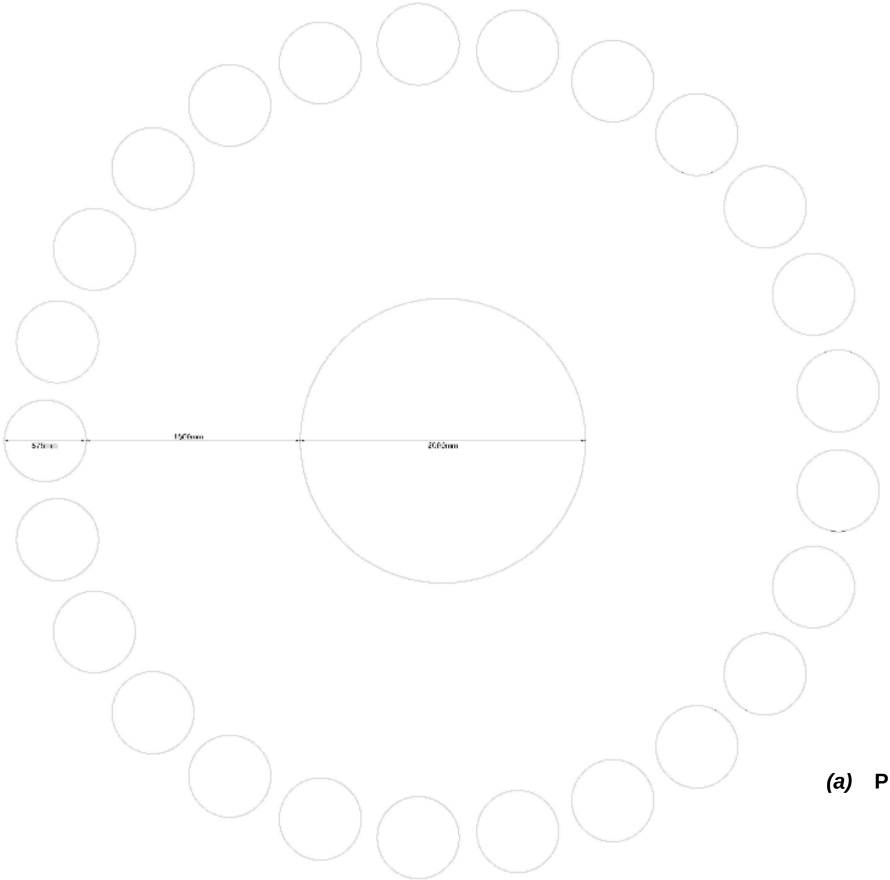
Figure 3: Pilot granulator at United Utilities plc, Ellesmere Port Wastewater Treatment Plant, Little Stanney, Chester, CH2 4HZ [Pictures facilitated by United Utilities plc].

Appendix A.1.2: Design of the lysimeters' station constructed at the College Farm, Cranfield University at Silsoe



***(b)* Side elevation**



***(a)* Plan view**

Figure A.1.1: Design of lysimeters station at Sand Pit Field, College Farm, Cranfield University, Silsoe, MK45 4DT.

Appendix A.1.3: Photographic record of the work conducted at the lysimeters station – Sand Pit Field (College Farm, Silsoe, MK45 4DT)

Figure A.1.2: Photographic record of lysimeters station at the College Farm; (a, b, c) construction (February 2008); (d) established crops and measurement of N_2O (May 2010); (e) view of the drainage and leachate collectors.

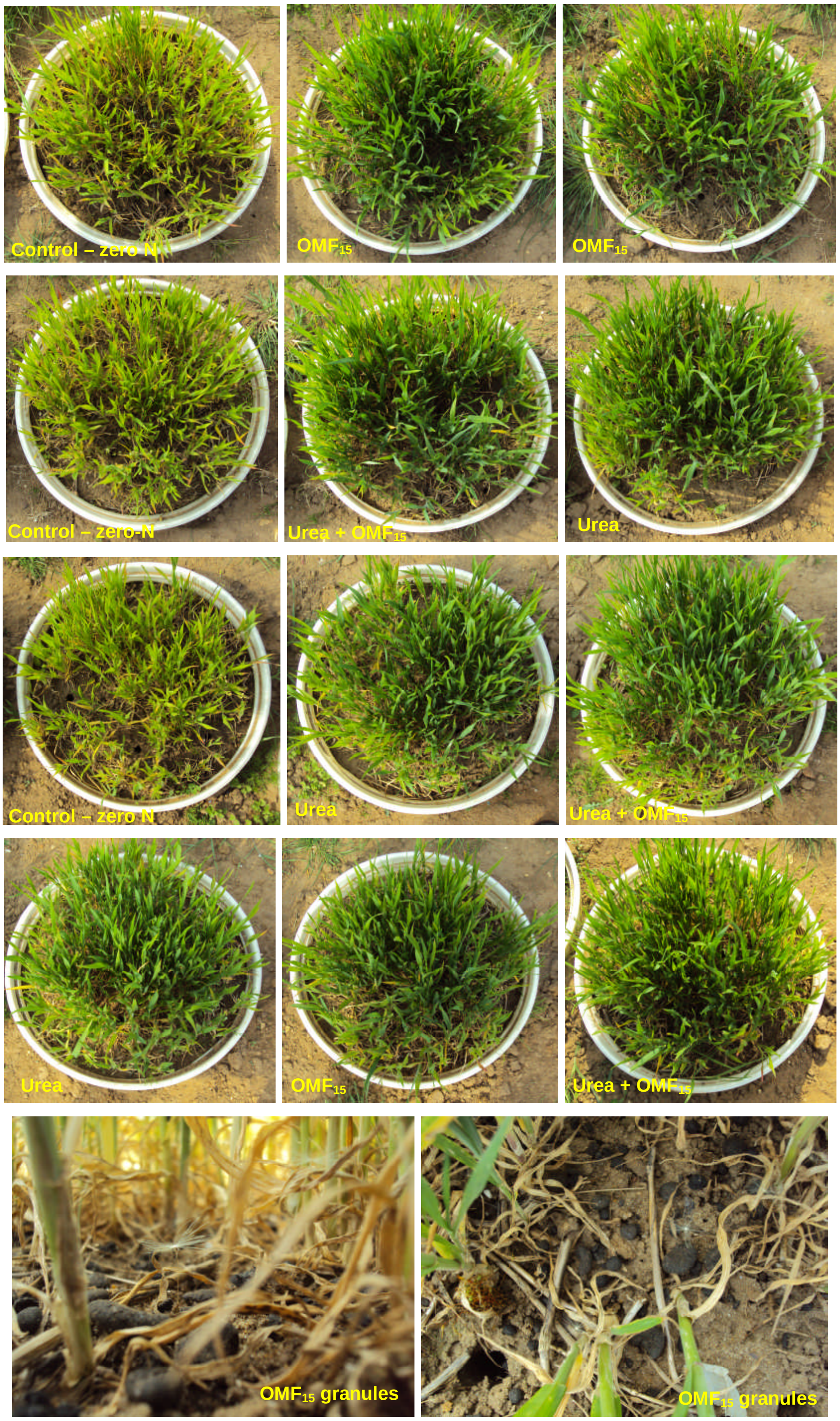


Figure A.1.3: Photographic record of the crop and treatments in the lysimeters station at the College Farm (April 2009) – 2nd winter wheat crop; and close-up of granules of OMF_{15} (bottom). (All treatments, except the controls, fertilised with 250 kg [N] ha^{-1}).

Appendix A.1.4: Proceedings of the Cranfield Multi-Strand Conference – Creating wealth through research and innovation, Cranfield University, 6-7 May 2008

Methodological approach to identifying the properties of a novel organomineral fertiliser – *Part II:* environmental aspects and OMF application [Paper No.: 133]

(*)**Antille, D.L.**; Sakrabani, R., and Godwin, R.J.
School of Applied Sciences, Cranfield University, Bedfordshire, MK43 0AL, UK.
(*)E-mail: d.l.antille.s05@cranfield.ac.uk

SUMMARY

This paper summarises the methodology used in this investigation to determine the potential environmental impact arising from the use of organomineral fertilisers (OMF) in agricultural land by focusing upon two main subjects: NO_3-leaching and N_2O-emissions. In addition, the paper describes the method that will be used for the evaluation of spreading fertiliser equipment. It highlights the importance of achieving a high degree of uniformity when applying biosolids to agricultural land as one of the main factors controlling the agronomic efficiency of applied nutrients. Although experimental data are not available yet, the experiments are under construction, and it is the aim of this paper to gain criticism on the proposed methodological approach. Experimental data will be statistically analysed using analysis of variance and least significant differences to compare means.

Key words: *nitrogen leaching, nitrous oxide emission, fertiliser spreading*

INTRODUCTION

The application of sewage-sludge to agricultural land is a highly regulated activity (Evans, 1998). It is governed by the EU Sewage Sludge Directive 86/278/EEC which is enforced in the UK through the Sludge (Use in Agriculture) Regulations 1989. These are complemented by a number of regulations such as The Code of Practice for Agricultural Use of Sewage Sludge and the Safe Sludge Matrix among others. The position of the UK Government towards recycling has been clearly indicated. In this respect, the Government has committed to reduce the amount of waste landfilled to 75% of that produced in 1995 by 2010, and to cutback CO_2 emissions by 20% in 2010 (Defra, 2007); thereby, imposing increasing restrictions to disposal through incineration and landfill.

Although the fertiliser value of sewage-sludge have been acknowledged (Milne and Cleveland, 1972); in practice, many farmers appear to be reluctant to applying biosolids to agricultural land. This is often due to the impracticality of having to deal with large volumes of materials to meet the nutrients' requirements of crops. The use of cakes in more recent years addressed, to certain extent, some of the problems associated with liquid sludges; e.g. cost of transport and application. However, the problem of delivering the desired application rates and achieving acceptable levels of uniformity across the working width of spreading fertiliser equipment, for instance, similar to those of mineral fertilisers applied with standard fertiliser spreaders, remains unsolved. This is aggravated by the fact that physical properties; e.g. particle size and composition of individual particles are not consistent. Uneven nutrient distribution can increase the risk of N-losses; e.g. nitrate leaching and gaseous losses, in areas where N is applied in excess of crop demand. The development of OMFs would contribute to address these issues by providing a product which has more consistent physical characteristics and known chemical composition (Antille et al., 2008).

The aim of this work is to describe the methodology that will be used to quantify the losses of N from the formulated OMFs through both nitrate (NO_3) leaching and denitrification via nitrous oxide (N_2O). In addition, the paper explains how the OMFs' physical properties will be assessed in relation to the distribution pattern during application and the spreading equipment.

METHODOLOGY

OMFs' physical properties

There are a number of properties that control both the motion of individual particles and the resultant spread pattern. Hofstee (1993) indicated that the most important properties are:

- ***a.*** particle size and particle size distribution;
- ***b.*** coefficient of friction;
- ***c.*** aerodynamic resistance;
- ***d.*** coefficient of restitution; and
- ***e.*** particle strength.

From these, ***a***, ***b***, and ***c***, have the greatest influence on the spreading pattern (Hofstee, 1993). In addition, particle strength can alter the particle size distribution and affects the spreading pattern if segregation takes place (Bradley and Farnish, 2005).

Preliminary results showed that OMFs have a bulk density of 0.58-060 t m^{-3}; this value is approximately 10% higher than that of digested cake. It appears that the blending process, during the OMF production, results in increased bulk density of the final product compared to the cake. The measured bulk density of granules of urea fertiliser gave an approximate value of 0.78 t m^{-3}. The particle size distribution was determined by sieving a sample of OMF and then weighting the sieved material; this was done for a number of sieves sizes ranging from < 1 mm to >5.6 mm in diameter (**Figure 1**).

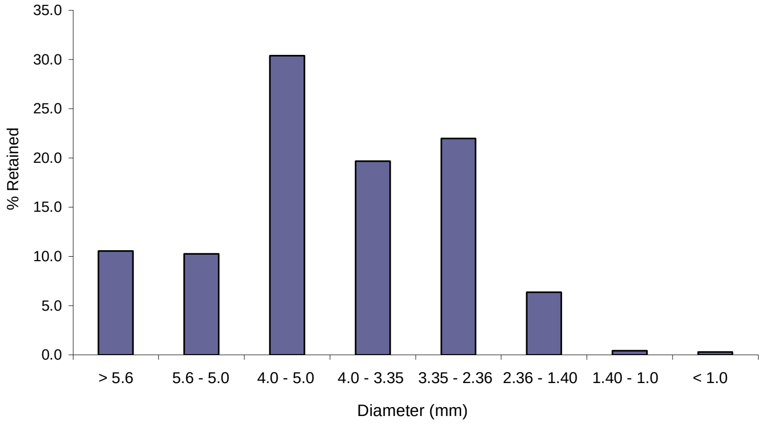


Figure 1: Particle size distribution of a sample of OMF.

The same was done for urea which gave, as expected, a much uniform particle size distribution with more than 92% of the particles in the range of 2 to 4 mm in diameter. Given that just over 40% of OMF particles fell into the desired size; i.e. 2-4 mm, a decision was made to discard all OMF particles outside this range in order to obtain a similar particle size distribution as urea. This approach means more processing during the OMF production but will ensure more uniformity in the final product (**Figure 2**).

Figure 2: A picture showing OMF particles in the range 2 to 4 mm in diameter [Source: United Utilities plc].

This work is concerned with the optimisation of the particle shape, size, and size distribution, as these parameters can be easily adjusted during the OMF production. These properties will be then assessed by means of a spreading trial in the field. Details of this trial are given in the following section. In addition, it would be an advantage to measure the OMF breaking force to determine the relationship between the OMF particle strength and particle size. This relationship would provide a valuable indication on whether the OMF becomes stronger or weaker as the particle size is increased. Various strength measuring techniques are described by Hoffmeister (1979) and Rutland (1986).

OMF application

The most widespread methodology for measuring distribution uniformity and calibrating granular broadcast fertiliser spreaders is given by ASAE (1999) S341.2. The advantage of this method is that it allows to determine the performance of fertiliser spreaders when used for the application of granular fertilisers, and to compare different distribution patterns. The test consists of two parts:

1. determination of application rate, and
2. determination of distribution pattern.

The rate is determined by measuring the amount of material applied divided by the area. The spread pattern indicates the degree of uniformity of distribution of fertiliser across the working width. This is determined by collecting and weighting fertiliser particles captured in trays placed across the swath being spread. The OMF products have been formulated for application rates of 1.2-1.4 t ha^{-1}; thus, the spreading equipment; i.e. Bredal K105 and Amazon ZA-M, will be first adjusted to deliver the desired rates and then the distribution pattern will be determined.

Comparisons will be made with a standard fertiliser; e.g. urea. This test will provide valuable information regarding the spreading behaviour of this material, its interaction with standard spreading equipment, and the need for improving the OMF’s physical properties.

Nitrogen leaching

Losses of applied OMF-N will be determined using lysimeters which were recently constructed at the College Farm at Cranfield University at Silsoe (**Figure 3**). Quantifying N-losses is important to anticipate the potential environmental risk associated with the use of OMF. The design of the lysimeters is shown in **Figure 4**.

The experiment comprises the use of a sandy loam soil, OMF_{15}, urea, and a combination of urea and OMF_{15} used as fertilisers materials which will be applied at only one rate of 250 kg N ha^{-1}, and a control with no fertiliser added, and two crops; i.e. spring wheat and grass. This design gives a total of 25 lysimeters. Each treatment will be replicated three times to facilitate the statistical analysis.

Figure 3: Overview of lysimeters' facility at Silsoe Farm following its construction in 2008.

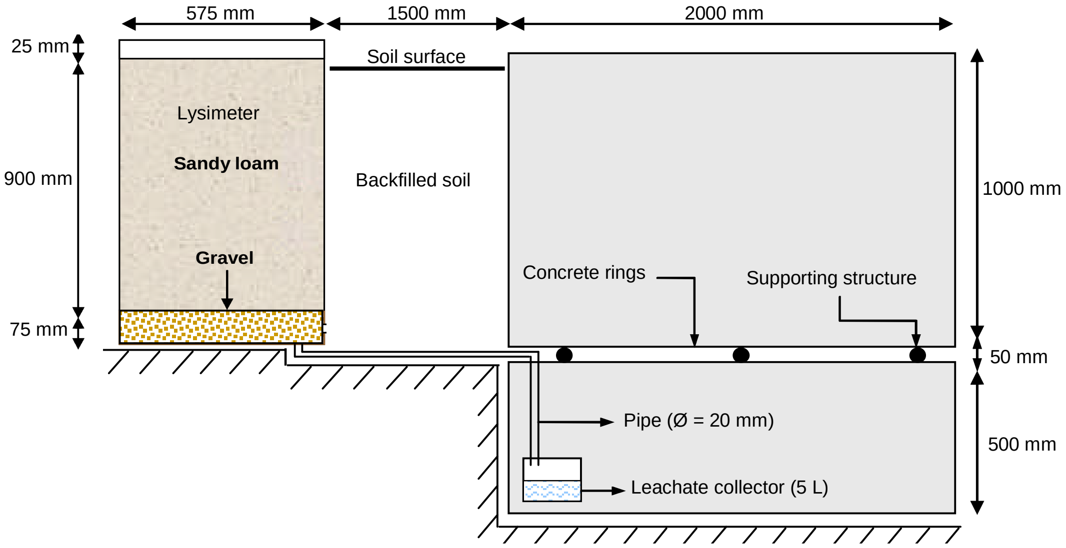


Figure 4: Diagram illustrating the lysimeters' design (side elevation – not to scale).

Leachate will be regularly collected for determination of NO_3^-. In addition, soil available-N will be determined before fertiliser application and at the end of the growing season to aid establishing a nitrogen balance in the soil. This information will be linked to measurements of N_2O emissions which are explained in the following section.

Nitrous oxide emissions

Nitrous oxide is a greenhouse gas for which inventories of emissions are needed to comply with the Kyoto Protocol 1997 (Smith and Dobbie, 2001). At present, there is limited amount of information available on N_2O-emissions after sewage-sludge application to agricultural land (Le, 2008). There is also no evidence of research being undertaken to determine N_2O-emisions after OMF application. The purpose of this experiment is to quantify N_2O-emissions following OMF application on spring wheat and grassland. Measurements will be taken for a period of 24 months to account for temporal variability. In this experiment, an automated closed-chamber developed by Smith and Dobbie (2001) will be used. The chambers will be placed on top of the lysimeters to facilitate the linking of these data to that of leaching. Samples will be collected for gas chromatographic analysis at ADAS-Boxworth. Full details of the chambers are given in Smith and Dobbie (2001).

CONCLUSIONS

The development of OMFs will contribute to address some of the issues related to the application of sewage-sludge to agricultural land. Improving the physical characteristics of the product is crucial to delivering the desired application rates. This is important to optimise the economic return from the use of fertilisers and reduce nutrient losses. Quantification of N-losses is important to develop appropriate fertiliser application strategies, protect the environment, and ultimately, improve the agronomic efficiency of applied nutrients.

ACKNOWLEDGEMENTS

The authors would like to thank the sponsoring company, United Utilities plc, and the Engineering and Physical Sciences Research Council (EPSRC) for their financial assistance, Cranfield University staff for their help during the construction of the experiments, and Dr. Rachel Thorman (ADAS-Boxworth) and Mr. Anthony Dale (Dale Contractors) for many useful suggestions concerning this work.

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Appendix A.1.5: Proceedings of the 16th Nitrogen workshop: connecting different scales of nitrogen use in agriculture, University of Turin, Italy, 28 June – 1 July 2009 [In: Grignani et al., 2009 (Eds.)]

NITROGEN BUDGET FOLLOWING APPLICATION OF NUTRIENT ENRICHED BIOSOLIDS TO AGRICULTURAL LAND: A LYSIMETER CASE STUDY

D.L. Antille[1], R. Sakrabani[1], R.J. Godwin[1]

[1] *School of Applied Science, Cranfield University, MK43 0AL, Cranfield, Bedfordshire, UK, Email: d.l.antille.s05@cranfield.ac.uk*

Introduction

The production of sewage sludge (biosolids) in the UK is *c.*1.5 million tonnes (dry-solid basis) per annum (Defra 2007). Approximately 60% of this amount is treated to standards suitable for agricultural recycling, 20% is disposed of by incineration, and the remaining 20% is used mainly for landfill and land reclamation. Recycling to agricultural land is usually regarded as the best practicable environmental option having also lower costs compared with the other disposal alternatives. In order to secure the agricultural route for disposal, a novel technique to produce urea enriched biosolids, namely organomineral fertilisers (OMF), was developed by a major water company in the UK. This consists of coating the biosolid in the form of granules (2 – 4 mm in diameter) with urea (46% N) to increase the existing N:P ratio of the biosolid; thereby, improving its nutrient composition. This technique was used to produce an organomineral fertiliser having 15% N, 4% P_2O_5, and 4% K_2O. This product is referred to as OMF_{15}. The purpose of this work was to investigate the N budget following application of OMF_{15} (15% N), urea (46% N), and a combination of urea and OMF_{15} in the ratio 1:4 to spring wheat (*Triticum aestivum L*) in lysimeters.

Materials and Methods

The work was conducted in lysimeters having 575 mm in diameter and 1000 mm in depth. These were filled with a sandy loam soil having 60% sand, 28% silt and 12% clay. The experiment comprises the use of OMF_{15}, urea, and a 1:4 mixture of urea and OMF_{15} applied to spring wheat (*Triticum aestivum L*) at a single rate of 250 kg [N] ha^{-1} which was split into two applications of 125 kg [N] ha^{-1} each. The fertiliser was applied on the soil surface when the crop was at growth stage 39-40; i.e. flag leaf ligule visible (Tottman and Broad 1987). Crop establishment was recorded on 1st May 2008. Leachate was collected after every rainfall event for determination of nitrate [NO_3^-] (Burkard 1995) and the amount of leachate measured and recorded. Soil analyses were also performed for determination of initial soil organic matter content [SOM], soil mineral N and total N (MAFF 1986; Methods no. 56, 53, and 49 respectively) before the fertiliser application and post-harvest. To aid the N budget calculation, N content in grain (MAFF 1986; Method no. 48) and grain yield were also determined. The straw was removed from the soil after the harvest. Measurements of nitrous oxide (N2O) emissions were performed using the static chamber technique as described in Thorman et al. (2007). In this experiment, however, larger chambers were used (630 mm x 630 mm x 250 mm) and 60 minutes were allowed before taking the sample. N_2O concentration in the sample was determined by gas chromatography. The N_2O increase (ppm-v) over the 60 minutes period was subsequently used to estimate the N_2O emission rate. Background concentration of N_2O in the air was also measured. Fluxes were measured daily for a period of 4 days following N fertiliser application and every 2 weeks thereafter. Measurement of N_2O requires sampling to be done over a period of one year to account for temporal variability in N_2O emissions and also to comply with IPCC specifications.

Results

The nitrogen budget was estimated using the equation shown below. N losses by volatilisation were considered negligible although this is not totally true as these can be significant when using urea as a source of nitrogen especially when it is not incorporated (Darwich 1998). Sutton et al. (1995) reported that in arable rotations and in the absence of manure applications emission and deposition of ammonia are approximately the same. For the purpose of this work, N volatilisation is excluded from the equation. Atmospheric deposition of N is not considered as it was difficult to find a precise value for the experimental site.

N Balance = [N-Fertiliser + N-Mineralisation] – [N Off-take + N_2O emissions + N-Leaching].

The calculated N balances for the 3 treatments and the control are shown in **Tab.1** below.

Tab. 1. N balances for spring wheat (*Triticum aestivum L*) grown in lysimeters for a period of 135 days following application of OMF_{15}, urea, and urea and OMF_{15} (1:4 dry mixture) at a single N rate of 250 kg [N] ha^{-1}, and a control with no fertiliser. Note: all values are expressed in kg [N] ha^{-1}.

Treatment	N-rate	N-Mineralisation	Off-take	N_2O emission	N- Leaching	Balance
Control	0	94.9	97.1	4.34	0.19	**-6.73**
OMF_{15}	250	94.9	183.9	4.51	0.12	**156.37**
Urea	250	94.9	181.8	3.96	0.25	**158.89**
OMF_{15}+Urea	250	94.9	177.4	4.62	0.10	**162.78**

N mineralisation was estimated using a mineralisation rate of 0.704 kg [N] ha^{-1} day^{-1} which was obtained in an incubation experiment run in parallel maintaining the soil at field capacity and at 25ºC over a period of 3 months. This gives a total of 94.9 kg [N] ha^{-1} for 135 days and corresponds to 1.87% of the total N in the soil. This N mineralisation rate may overestimate the amount of soil mineral N as it was obtained in controlled laboratory conditions. The total N content in the soil remained unchanged after the harvest in all treatments as there were not significant differences (p=0.370) with respect to the initial value at the start of the experiment (mean TN values of 0.145% and 0.143% respectively; $LSD_{5\%}$=0.0083). The differences in N off-take by the crop were due to differences in crop yield and total biomass production. Overall, N_2O emissions were statistically similar (p=0783) for both the control and the treatments. However, they did differ between sampling events (p=0.001). This indicates that there is an effect of the fertilisation on the N_2O emissions immediately after application but the effects are not reflected when considering the entire 135 days period. The lower overall value of N_2O emissions recorded for urea may be indicating that other N losses (e.g. volatilisation) took place at a faster rate compared to denitrification therefore reducing the scope for N_2O emissions. In addition, no significant differences were found between the control and the treatments and between the treatments with respect to the amount of leachate (p values of 0.507 and 0.566 respectively). The same was observed for the N concentration in the leachate (p values of 0.292 and 0.827 respectively). However, significant differences were observed for N concentration in the leachate between sampling events (p=0.027). Similarly, this indicates an effect of fertiliser application on the N content in the leachate. However, this is not evident when analysing the whole period. It is clear that during the crop growing season, the largest N removal from the soil is due to the crop up-take. Webb et al. (2004) reported annual losses of N_2O in arable fields between 0.1-1.8 kg [N] ha^{-1} y^{-1}. The emission values shown in **Tab.1** appear to be significantly higher although they only correspond to a limited period of time. During this period, indirect emissions of N_2O (e.g. emissions linked to leached-N) are expected to be negligible as N losses by leaching accounted for less than 0.01% of the total N applied. A large surplus of N balance after the harvest increases the scope for N losses; particularly, during the winter time which was not considered in this analysis. Webb et al. (2004) concluded that the largest potential reduction in N losses in arable situations is minimising N leaching. Therefore, it is important to account for this surplus balance in subsequent N applications in order to reduce the scope for direct and indirect N_2O losses and N leaching.

Conclusions

Losses of N by denitrification (N_2O) and leaching appeared to be consistently lower than N up-take by the crop during the crop growing season (spring and summer) under the prevailing experimental conditions. It is important to quantify these losses over a longer period of time to account for temporal variability. Large surplus of N in fertilised soil may lead to increased N losses during autumn and winter. This excess of N needs to be considered in subsequent N fertiliser applications.

Acknowledgements

Acknowledgements are due to United Utilities plc, the Engineering and Physical Sciences Research Council (EPSRC), Staff at Cranfield University, and Dr RE Thorman (ADAS-Boxworth).

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Appendix A.1.6: Soil nitrous oxide (N_2O) emission measurements – using manually operated soil chambers for analysis of the chamber headspace by gas chromatography

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(EngD Thesis – Diogenes Antille, Cranfield University)

Soil Nitrous Oxide (N2O) emission measurements: using manually operated soil chambers for analysis of the chamber headspace by gas chromatography

INTRODUCTION

The closed, static chamber method is used to measure the emission of N_2O from soil. A PVC chamber box is inserted to a depth of approximately 5 cm (i.e. sufficient to produce an adequate seal). Background measurements of the gases of interest are taken by manually sampling the atmosphere around the experimental plots. To begin flux measurements, a lid is placed on top of the chamber, enclosing the atmosphere above the soil and within the chamber. The time at which this is done is noted. The chamber lid is left on for a predetermined amount of time, usually 40 minutes. The accumulation of N_2O within the chamber is measured by manually taking a gas sample from the chamber and sending the sample for analysis by gas chromatography (at ADAS Boxworth). The N_2O increase (ppmv) over the incubation period (minutes) is used to calculate the N_2O emission rate.

MATERIALS AND EQUIPMENT

1. Cutting square frame.
2. Plastic headed mallet to “hammer” the cutting square frame into the soil.
3. Wooden block (at least 45 cm. In length) to prevent damage to the cutting frame.
4. Spirit level.
5. Pallet knife/spade or similar to further define the slots left by cutting frame.
6. Water container with tap (25 litres) filled with water.
7. Watering can/plastic beaker/jug (c.1 litre) etc. To transfer water from container to chamber groove.
8. Static chamber boxes.
9. 23 Gauge needles (Fischer Scientific – catalogue no. SZR-275-510P), 50 ml glass syringe (Fischer Scientific – catalogue no. SZR-280-015V) and 50 ml plastic back up syringe (Fischer Scientific – catalogue no. SZR-205-160T). Take spare syringe and needles into field. Rubber seals (Fischer Scientific – catalogue No.: FB 57895)
10. Silicone grease to lubricate the glass syringes (Fischer Scientific-catalogue no. LUB-450-U)
11. Accurate watch or stopwatch.
12. Proforma sheets (site details and data, see Appendices) and clipboard.
13. Marker pen and brio pens.

PROCEDURES

1 Safety considerations

The method involves bending to sample chambers at ground level, take care to avoid back strain/injury. As hypodermic needles are used to sample ambient and chamber headspace gases, operators should take care not to “prick” themselves. Should blood be drawn following an accidental “pricking”, the needle must be disposed of in a sharps bin to comply with health and safety regulations.

2 Measurements: planning

The flux of N_2O is determined by measuring the increase in N_2O concentration (above the concentration of the ambient air) in an enclosed chamber over defined period of time. In most situations, the increase in N_2O concentration is linear over a 40-50 minute period. Beyond this however, and depending on a variety of factors, the rate of increase tends to decline. As only one field measurement is made of the N_2O concentration, it is crucial to plan the timing of operations to allow for placing chambers and withdrawing the samples. Exceeding the suggested enclosure period greatly increases the risk of non-linearity and hence underestimating the flux. Work out the timing of operations based on the trial design. As gas sampling takes the longest time, plan by working back from an enclosure period of 40 minutes per chamber. Allow 1 minute between enclosing each chamber to ensure enough time for sampling. Carry out operations by block, but randomise the order in which blocks are measured on different days, as N_2O fluxes do show diurnal variation. If possible carry out all measurements between 9 and 11 am when differences in soil temperature are at a minimum. In all cases, record the time of sampling on the proforma. Individual gas vials should be labelled with the same unique sample identifier as on the gas sampling proforma. The code should include a reference to the name of the field site and the project code. Numbering should be sequential and the same numbers should not be used for the same experiment. Vials should be marked on the vial cap with permanent pen. Both before and after collection it is good practise to place the gas vials in numerical order in a suitable container; e.g. a labelled polystyrene tray.

3 Measurements from field plots

3.1 Complete the Site Details proforma (Appendix 1), describing the site, weather conditions, and any special features that may be use when it comes to analyses of the results, e.g. rabbit droppings inside chamber, description of the soil conditions etc. Complete the Gas Sampling proforma (Appendix 2) during sampling. An example gas sampling proforma is shown in Appendix 3 of this document.

3.2 Measurements of N_2O should be made from randomly determined positions (avoiding features such as tramlines) in the appropriate field location.

3.3 Press the chambers into slots (previously made by a spade or by hammering in and removing a square steel frame) in the soil to a depth of approximately 5 cm. Once the chamber is installed, the inside and outside edges need to be tamped down to ensure good seal.

3.4 A spirit level should be used to ensure that the chambers are inserted into the ground to give a level top edge. This is important so that water in the channel running around the chamber top makes a gas-tight seal when the chamber lid is fitted.

3.5 Measure the height of the chamber from the soil surface to the highest part of the chamber, at all 4 corners and record on the proforma.

3.6 Once the chamber is in position, add enough water to the groove so that the base of the groove is completely covered. Place the lid on the chamber noting the exact time of enclosure in the proforma. Top up the water in the groove if necessary, first removing any debris in the groove, which may prevent the formation of a gas-tight seal.

3.7 The chambers should stay in place throughout the experiment, although they will need to be removed prior to farm operations e.g. fertiliser application, cultivations, etc and replaced as soon as possible after. Number the chambers and mark their positions. The long-term position of the chambers in the field is not critical, therefore, if removed they do not need to be returned to exactly the same position.

3.8 The chambers should be enclosed for a 40-minute period.

Note any deviations on the proforma, but **do not** enclosed for more than 45 minutes.

3.9 Take a 20-ml sample of the headspace gas from each individual chamber as detailed below

3.9.1 Take a 50-ml glass syringe fitted with a 23G needle, pierce the septum in the lid and slowly remove 50 ml of the headspace gas without withdrawing the needle.

3.9.2 Depress the plunger to force this sample back into the chamber and repeat several times to ensure that a representative gas sample is taken.

3.9.3 Slowly withdraw another 50 ml sample and remove the syringe from the chamber. Watch that the plunger does not retract into the syringe body, meaning that the gas was sampled too quickly; i.e. not at atmospheric pressure, and consequently, that the sample volume collected is less than 50 ml.

3.9.4 Expel some gas sample, reducing the sample volume in the syringe to 20 ml, and then pierce the septum of the appropriate labelled gas vial. As the vial is pierced, the gas will automatically be withdrawn from the syringe to equalise the pressures in the vial and syringe.

3.9.5 Push the last few ml in and allow the syringe plunger to return to rest, normally at 3-4 ml. Ensure that the vials are not over-pressurised.

3.9.6 Note down the gas vial identifier, such that the vial and N_2O concentration in the particular chamber headspace can be matched following subsequent analysis by gas chromatography.

3.9.7 Record the time that the gas samples are taken on the proforma.

4 Linearity check

To check on the linearity of gas accumulation within a chamber´s headspace, underlying the principle of the methodology, select 2 chambers at random each month, and at least weekly during the more frequent sampling after fertiliser application). Take a time series of samples following closure at 1, 15, 30, 45 and 60 minutes and submit for analysis.

5 Measures to permit sampling throughout the growing season

5.1 The water seals allow a series of chambers to be stacked on top of each other as the crop increases in height. Once the crop has reached the top of the in situ chamber i.e. the chamber lid can no longer be fitted without crop damage, fit another chamber onto the in situ chamber for sampling. Fill both grooves with water; i.e. that between the 2 chambers and that between the extra chamber and the lid. Put the lid on the sample as usual.

Additional chambers can be added if the crop height necessitates it. After each gas sampling, retrieve all additional, stacked chambers that have been fitted, leaving only the original base one. Do not leave inside the plot.

5.2 At least 1 week before (to ensure that analysis results will be available) the first scheduled gas sampling with each additional stacked chamber, a linearity test must be carried out to establish what the appropriate chamber closure time should be. Two chambers should be selected at random from a control plot and two from a fertilised plot. A time series of samples be taken following closure time at 1 min, 15, 30, 45, 60, 70 and 90 min. Use an enclosure time that is on the linear part of the graph.

6 Ambient N_2O concentrations at the site

Make an assessment of the ambient N_2O concentration of the experimental area, as follows:

6.1 Collect (in pre-evacuated gas vials) eight 20-ml ambient gas samples from the experimental plot area. These samples should be collected away any roads and the soil surface to avoid contamination from car exhausts or soil efflux respectively. Take the ambient samples from about one metre above the ground; i.e. approximately around waist height.

6.2 Vials should be labelled with the name of the field site and the project code and a unique sample identifier, such that these samples can be identified as ambient. In the notes section of the proforma record these samples as AMBIENT.

7 Completion and sample submission

7.1 Once all samples have been taken, remove the lids from the chambers and place some distance from the chamber (approximately 1-2 m), so as to avoid a preferential rain shadow around the chamber.

7.2 The glass gas vials can be easily broken, so ensure that they are well packaged to avoid damage in transit. A photocopy of the proforma sheets should be kept by the gas sampler for ready reference.

7.3 Send samples as soon as possible after collection by courier Helen Kingston at ADAS Boxworth, together with the proforma sheets. Prompt despatch of the gas vials is important. Vials containing a known concentration of standard gas (standards) are added to the batch of vials at Boxworth on arrival. The standards then permit correction for gas loss if there is any delay in analysis by gas chromatography.

7.4 The gas samples will be analysed by gas chromatography.

8 Calculation of results

8.1 The automated gas chromatography equipment will analyse the N_2O concentration of field and ambient samples and the data will be copied to Dio Antille.

8.2 A spreadsheet will be provided for calculation of the N_2O flux. Input data required are: the chamber enclosure start end times; the increase N_2O concentration; and the chamber height. Please call (Dr Rachel Thorman at ADAS Boxworth, 01954-268256) if you have any queries.

Appendix 1: Proforma for gas sampling for analysis by GC

Experiment Code:	
Experiment Title:	
Site Name:	
Field Name:	
Sampling Date:	
Number of Ambient and Time Taken:	
Number of Stored samples and concentration (ppm): (To be entered by Boxworth lab staff)	
Weather during sampling	Raining/ Dry Hot/ Warm/ Cool/ Cold Calm/ Light breeze/ Windy
Soil conditions	Water on surface / Soil wet/ Soil moist / Soil dry
General Comments:	

Appendix 2: Records

Sample Identifier	Plot Number	Chamber Number	Chamber Height (cm)	Time Chamber on	Time Gas sampling	Notes

Appendix 3: Example data for N_2O gas sampling sheet

Sample Identifier	Plot Number	Chamber Number	Chamber Height (cm)	Time Chamber on	Time Gas sampling	Notes
TT-NT2605-001	6	1	15.5, 19.5 15.2, 19.3	10:54	11.:34	
TT-NT2605-002	6	2	20.3, 19.5 20.2, 19.9	10: 55	11:35	Rabbit pooh in chamber
TT-NT2605-003	6	3	15.5, 19.5 15.2, 19.3	10:56	11:36	
TT-NT2605-004	9	4	20.3, 19.5 20.2, 19.9	10:57	11:3	
Etc	etc	etc	etc	etc	etc	

APPENDIX CHAPTER 2

Appendix A. 2.1: Soil map of the area of Warrington (Lancashire, UK) – Brief description of the main soil associations encountered in the area.

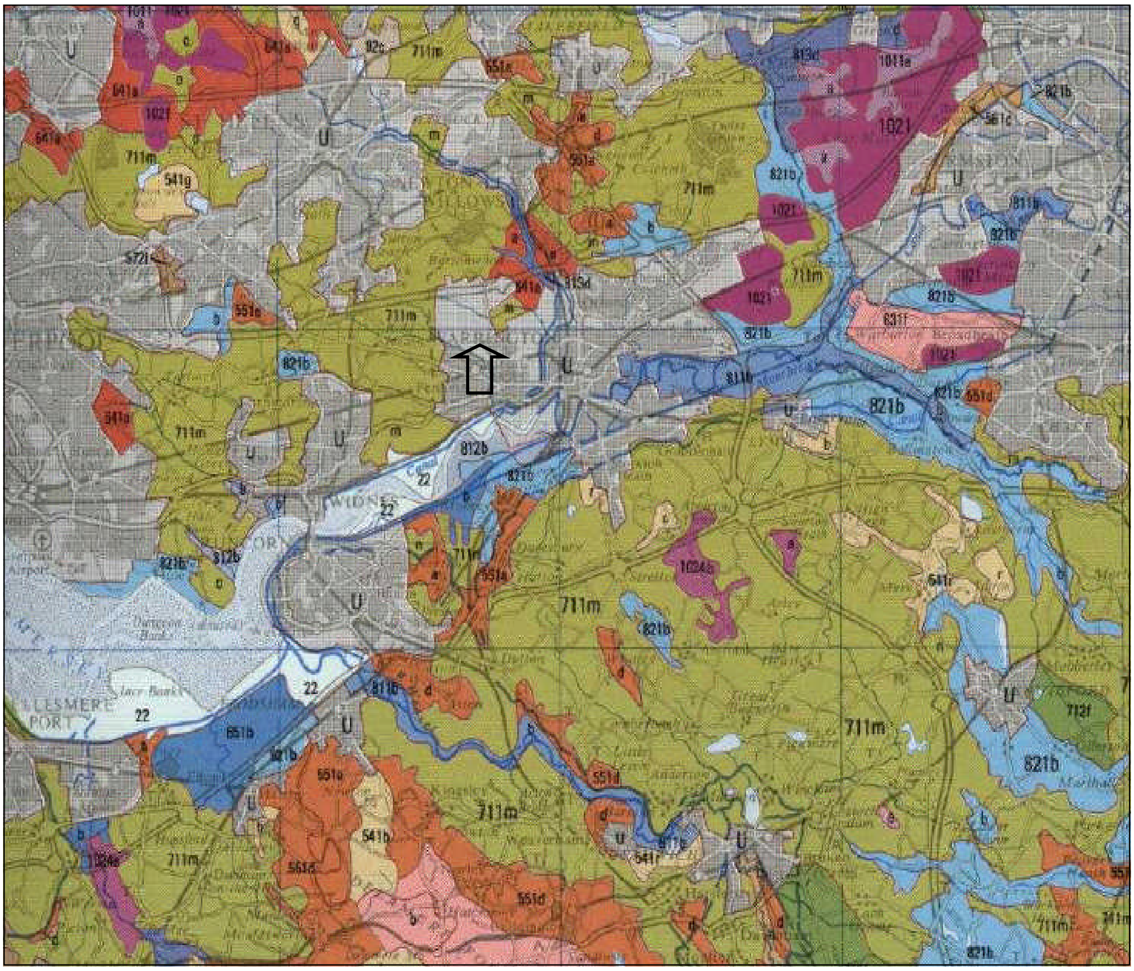


Figure A.2.1: Soil map of the area of Warrington (Lancashire), UK (Source: SSEW, 1983; sheet no.3) indicated on the map with an arrow. Salop 711m is the most representative soil association in the operating area of United Utilities plc [Scale: *c.* 10 mm ≈ 2.35 miles].

i. Salop association 711m (from Ragg et al., 1984)

The association consists primarily of stagnogley soils with slowly permeable subsoils in reddish drift mostly derived from Permo-Triassic rocks. There are also a small proportion of stagnogleyic argillic brown earths. The association is present in large areas of Midlands and Northern England. The Salop series; i.e. fine loamy and clayey soils associated with fine loamy over clay, occupies between ⅓ and ⅔ of the area.

Salop series is described in full in Jones (1983). Other series encountered include Clifton series; i.e. similar to Salop but fine loamy throughout, more common in Cheshire, Crewe series; i.e. clay loam or clay soils with increasing clay content with depth, Rufford series; i.e. coarse loamy over clayey, most commonly found bordering areas of sandy and coarse loamy soils in Lancashire and Cheshire, and Flint series; i.e. slightly stony clay loam soils. The majority of the soils under Salop association may show surface waterlogging due to slowly permeable subsoil and reduce surface runoff. The soils are slightly droughty for most crops but moderately droughty for grass. Although mix farming with cereals and fodder crops is common, these soils are typically used for grass production including dairy farming. The number of machinery work days in the autumn is adequate providing field drainage is present (*c*.50 days for a normal year with 675 mm of rainfall).

ii. Blackwood association 821b (from Ragg et al., 1984)

The association consists primarily of permeable sandy and coarse loamy soils in glaciofluvial drift. The association is commonly covers vast areas of Northern and Eastern England, Midlands, Northern Wales. The Blackwood series is slightly stony loamy sand with generally poor natural drainage. Other soil series encountered include Formby series; i.e. stoneless medium loamy sand in the top soil and medium sand in the subsoil, and Ollerton series; i.e. stoneless or slightly stony sandy loam or loamy sand and loamy sand or sand in the subsoil. Blackwood series is described in full in Hollis (1978) and occurs widely in Cheshire and to a lesser extent in Lancashire, Staffordshire, and Shropshire.

The majority of the soils under Blackwood association may remain waterlogged in the winter due to fluctuating groundwater table combined with excess rainfall, particularly, when the impermeable layer is shallow. However, most soils have field drainage installed and waterlogging is partially controlled. These soils have naturally a low fertility status but arable and horticultural crops can be cultivated with appropriate fertilisation levels. Main crops include cereals, although sugar beet and potatoes, and grass for grazing are also common. In drained soils with long term grassland, grazing is performed all year round. The number of machinery work days in the autumn is adequate providing field drainage is present (*c*.121 days for a normal year with 575 mm of rainfall). The profile available water for Blackwood series is *c*.125 mm for grass and winter wheat. The mean moisture deficit varies between 112 mm and 185 mm (from slightly droughty to very droughty) for grass, and between 83 mm and 121 mm for winter wheat (slightly droughty).

iii. Conway association 811b (from Ragg et al., 1984)

The association consists of fine silty soils commonly found on the floodplains of rivers and streams and shows mottles as they are affected by high groundwater levels. It is a widespread association linked mainly to areas prone to flooding and it occupies *c*.200 km^2 in Western England. In some places having continuous waterlogging, the soils have developed peat in the topsoil. The soils encountered within this association include Conway series; i.e. fine silty typical alluvial gley soils, Enborne series; i.e. similar to Conway but fine loamy, Eversley series; i.e. coarse loamy, and Kettlebottom series; i.e. coarse loamy over gravely. Other series include Clwyd; i.e. silty clay loam soils, and Fladbury; i.e. mainly clay soils. Conway series is described in full in Thompson (1982). Due to their water regime with persistent flooding and high water table, the majority of the soils remain under permanent grass. Drainage may be economically unviable in most cases whereas management for wildlife conservation is a potential option.

iv. Turbary Moor association 1021 (from Ragg et al., 1984)

Turbary Moor series is the main soil series encountered within this association which includes peat soils usually found on lowland raised bog peats whose characteristics were substantially modified following the installation of field drainage and fuel peat cutting. Other soils include those peat found in Longmoss association which are frequently inclusions of Turbary Moor. Longmoss has suffered from none or much less intensive cutting compared with Turbary Moor. These soil associations are described in detail in Avery (1955), Hall and Folland (1970), and Kilgour (1979). In terms of the soil water regime, Turbary Moor soils are generally well drained when aided by field drains and pumped ditches and behave as non-droughty soils for most crops. A number of crops are grown on peat soils particularly salad crops. Lime application is a common practice to maintain soil pH at acceptable levels for crop growth and copper deficiency is often reported (Ragg et al., 1984).

v. Milford association 541a (from Ragg et al., 1984)

Milford association encompasses relatively well drained soils which are fine loamy typical brown earths on interbedded siltstones, sandstones, and mudstones on moderate and steep slopes. Milford series is dominant and it was described in detail by Wright (1980) and Rudeforth et al. (1984) along with other series present in this association. Most soils in this association are occupied by permanent grasslands grazed by beef cattle and sheep, and some forage crops on less steep land. Soils are generally apt for cultivation except for the fact that they remain wet; i.e. at or above field capacity, for over 225 days per year.

Appendix A.2.2: The Safe Sludge Matrix

A copy of the 3rd Edition of the Safe Sludge Matrix (ADAS et al., 2001a) can be found in the CD enclosed in the following folder:

- EngD Thesis\Appendices\Appendix Chapter 2 Literature review

APPENDIX CHAPTER 3

Appendix A.3.1: Statistical analyses corresponding to Chapter 3: Product specification

A.3.1.1: Statistical analyses – particle size analyses

The statistical analyses corresponding to the particle size analyses can be found in the CD enclosed in the following folder:

- EngD Thesis\Appendices\Appendix Chapter 3 Product specification

A.3.1.2: Statistical analysis – bulk density fertiliser materials used in 2007

Table A.3.1: Analysis of variance – bulk density of fertiliser materials used in 2007 (prior to grinding)

Variate: Bulk density (kg m^{-3})

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Fertiliser_type	3	94369.21	31456.4	2413.65	**<.001**
Residual	4	52.13	13.03		
Total	**7**	**94421.34**			

Table A.3.2: Analysis of variance – bulk density of fertiliser materials used in 2007 (after to grinding)

Variate: Bulk density (kg m^{-3})

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Fertiliser_type	3	62374.67	20791.56	1398	**<.001**
Residual	4	59.49	14.87		
Total	**7**	**62434.16**			

A.3.1.3: Statistical analysis – bulk density fertiliser materials used in 2008

Table A.3.3: Analysis of variance – bulk density of fertiliser materials used in 2008

Variate: Bulk density (kg m^{-3})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Fertiliser_type	3	24390.27	8130.09	120.75	**<.001**
Residual	4	269.31	67.33		
Total	**7**	**24659.58**			

A.3.1.4: Statistical analysis – bulk density fertiliser materials used in 2009

Table A.3.4: Analysis of variance – bulk density of fertiliser materials used in 2009

Variate: Bulk density (kg m^{-3})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Fertiliser_type	3	46581.67	15527.22	262.71	**<.001**
Residual	4	236.42	59.1		
Total	**7**	**46818.09**			

A.3.1.5: Statistical analysis – bulk density fertiliser materials used in 2010

Table A.3.5: Analysis of variance – bulk density of fertiliser materials used in 2010

Variate: Bulk density (kg m^{-3})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Fertiliser_type	3	24582.11	8194.04	137.65	**<.001**
Residual	4	238.11	59.53		
Total	**7**	**24820.22**			

A.3.1.6: Regression analysis – relationship between particle diameter and particle density (biosolids granules)

Response variate: Particle_density
Fitted terms: Constant, Particle_diameter_mm

Table A.3.6: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	4420993	4420993	93.8	**<.001**
Residual	83	3911764	47130		
Total	84	8332757	99199		

Percentage variance accounted for 52.5

Standard error of observations is estimated to be 217.

Table A.3.7: Estimates of parameters

Parameter	estimate	s.e.	t(83)	t pr.
Constant	2306	103	22.34	**<.001**
N_Rate_Sq. Fertiliser Biosolids	-240.8	24.9	-9.69	**<.001**

A.3.1.7: Regression analysis – relationship between particle diameter and particle density (OMF$_{10}$)

Response variate: Particle_density
Fitted terms: Constant, Particle_diameter_mm

Table A.3.8: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	800272	800272	13.24	**<.001**
Residual	85	5136883	60434		
Total	86	5937156	69037		

Percentage variance accounted for 12.5

Standard error of observations is estimated to be 246.

Table A.3.9: Estimates of parameters

Parameter	estimate	s.e.	t(85)	t pr.
Constant	1743	125	13.9	**<.001**
N_Rate_Sq. Fertiliser Biosolids	-98.9	27.2	-3.64	**<.001**

A.3.1.8: Regression analysis – relationship between particle diameter and particle density (OMF$_{15}$)

Response variate: Particle_density
Fitted terms: Constant, Particle_diameter_mm

Table A.3.10: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	314482	314482	11.01	**0.001**
Residual	96	2742202	28565		
Total	97	3056684	31512		

Percentage variance accounted for 9.4.

Standard error of observations is estimated to be 169.

Table A.311: Estimates of parameters

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1541.4	58.3	26.45	<.001
N_Rate_Sq. Fertiliser Biosolids	-31.23	9.41	-3.32	0.001

A.3.1.9: Regression analysis – relationship between particle diameter and particle density (urea)

Response variate: Particle_density
Fitted terms: Constant, Particle_diameter_mm

Table A.3.12: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	2798940	2798940	73.52	**<.001**
Residual	102	3882955	38068		
Total	103	6681894	64873		

Percentage variance accounted for 41.3.

Standard error of observations is estimated to be 195.

Table A.313: Estimates of parameters

Parameter	estimate	s.e.	t(102)	t pr.
Constant	2780	158	17.56	**<.001**
N_Rate_Sq. Fertiliser Biosolids	-362.7	42.3	-8.57	**<.001**

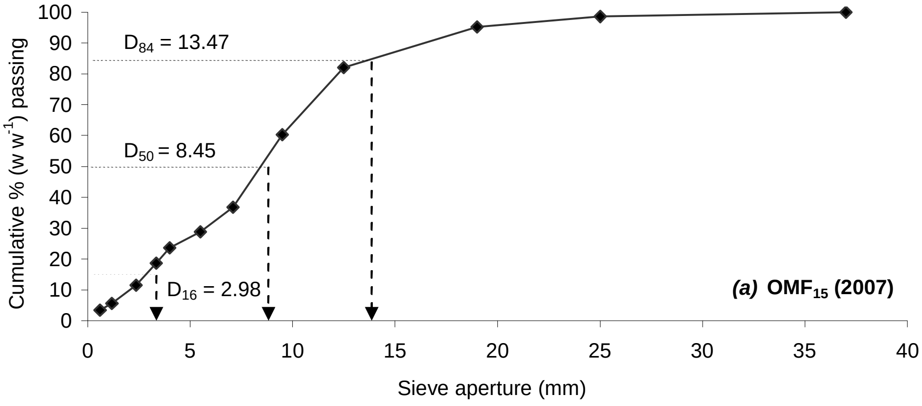
A.3.1.10: Statistical analysis – compression test (breaking force urea particles)

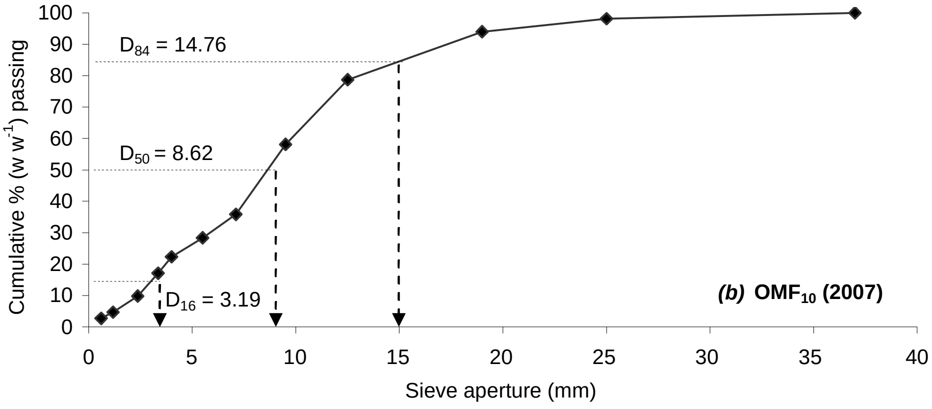
Table A.3.14: Analysis of variance – breaking force required for particles of urea

Variate: Breaking force (*N*)					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Particle size[*]	2	104.18	52.09	332.49	**<.001**
Residual	3	0.47	0.16		
Total	5	104.65			

[*]Particles in the range 2.36-3.35 mm, 3.35-4.00, 4.00-5.50 mm

Appendix A.3.2: Granulometric distribution curves of the fertiliser materials used in the experimental work 2007 – 2010





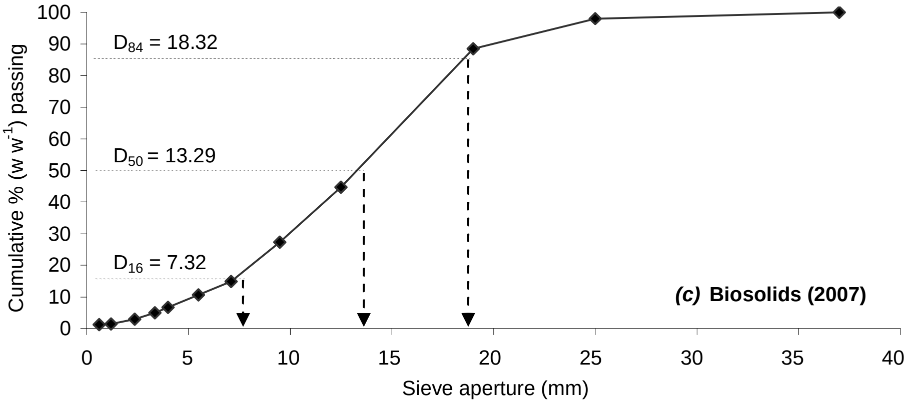


Figure A.3.1: Granulometric distribution curves showing the percentiles D_{16}, D_{50} and D_{84} corresponding to (*a*) OMF_{15}, (*b*) OMF_{10} and (*c*) biosolids supplied in 2007 prior to grinding.

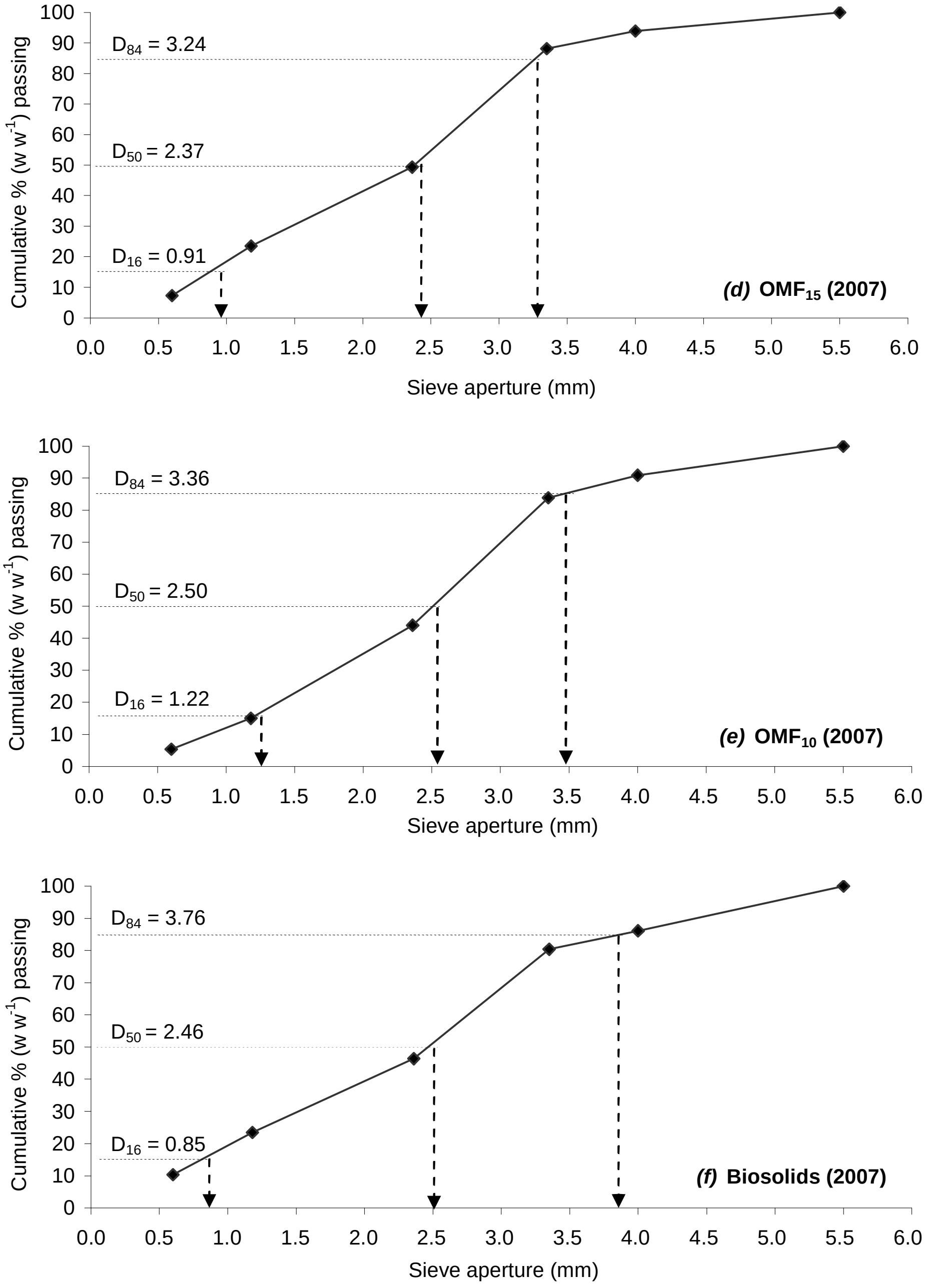


Figure A.3.2: Granulometric distribution curves showing the percentiles D_{16}, D_{50} and D_{84} corresponding to (*d*) OMF_{15}, (*e*) OMF_{10} and (*f*) biosolids supplied in 2007 after grinding.

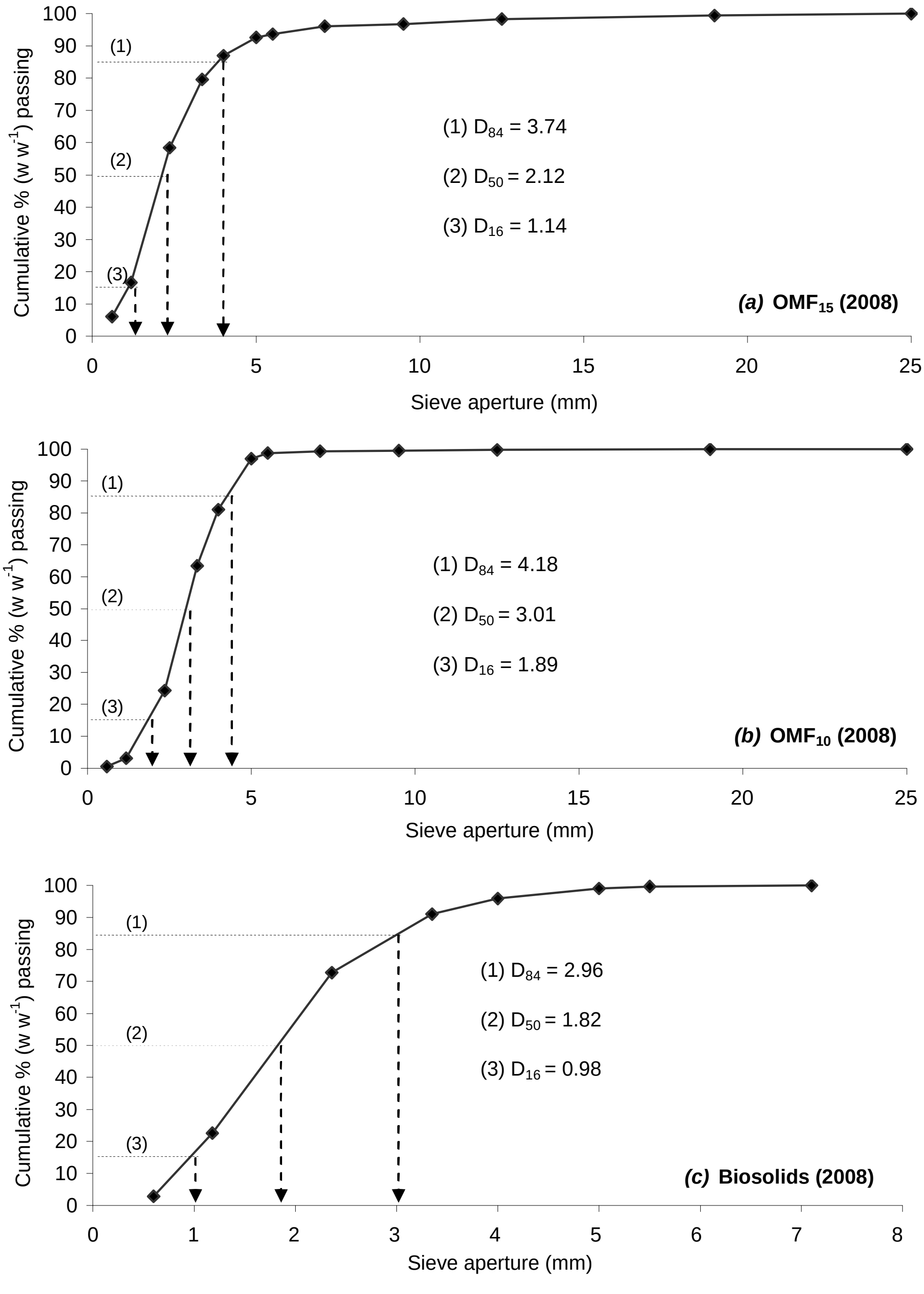


Figure A.3.3: Granulometric distribution curves showing the percentiles D_{16}, D_{50} and D_{84} corresponding to (*a*) OMF_{15}, (*b*) OMF_{10} and (*c*) biosolids supplied in 2008.

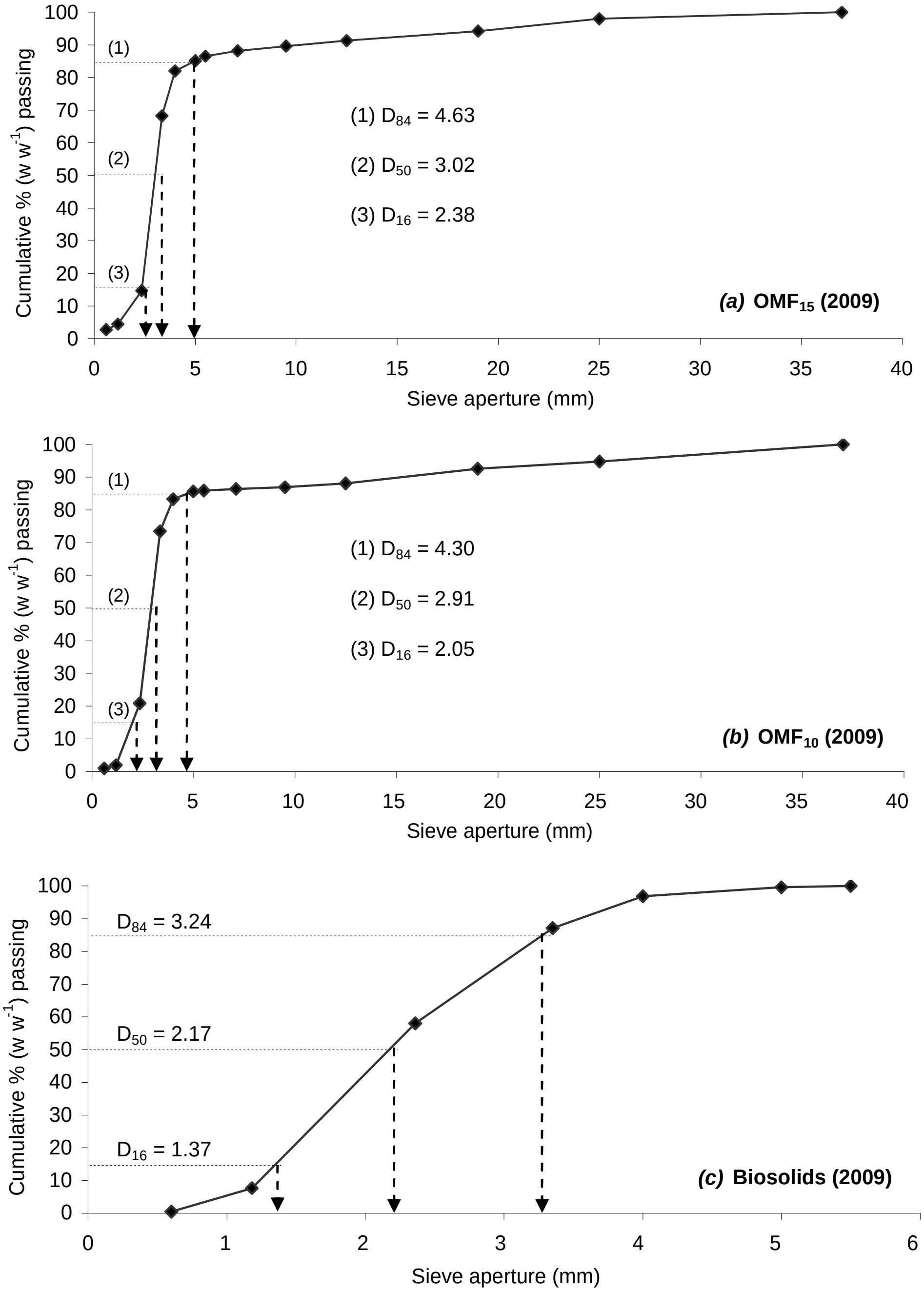


Figure A.3.4: Granulometric distribution curves showing the percentiles D_{16}, D_{50} and D_{84} corresponding to (*a*) OMF_{15}, (*b*) OMF_{10} and (*c*) biosolids supplied in 2009.

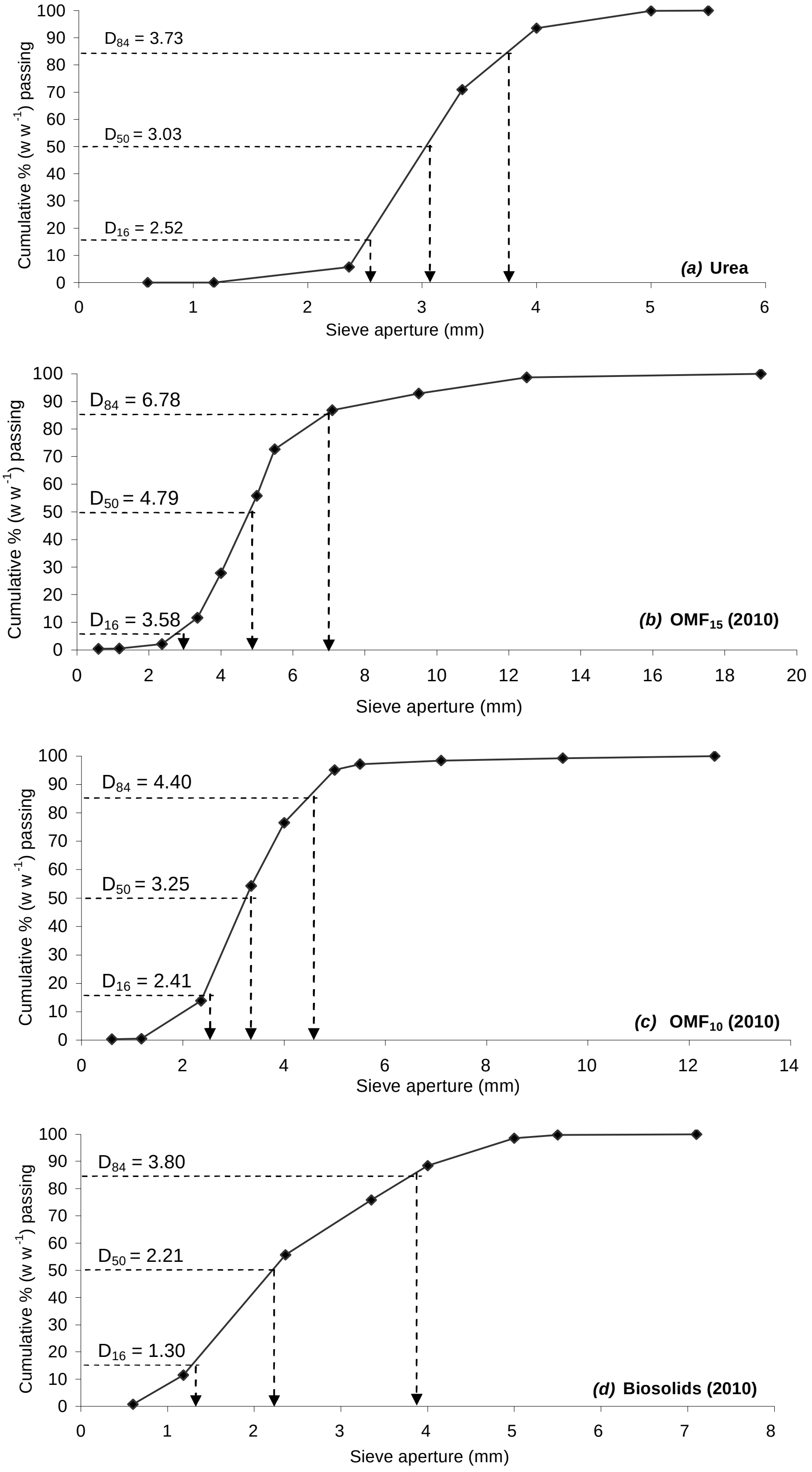
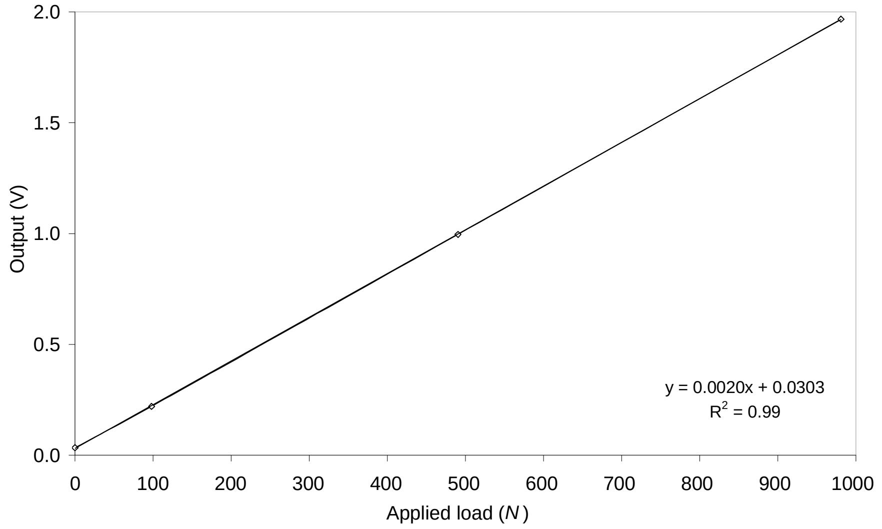


Figure A.3.5: Granulometric distribution curves showing the percentiles D_{16}, D_{50} and D_{84} for the fertiliser materials used in 2010 including urea; (*a*) urea, (*b*) OMF_{15}, (*c*) OMF_{10} and (*d*) biosolids granules.

Appendix A.3.3: Calibration curves – Instron 1122 (Instron, 1975).



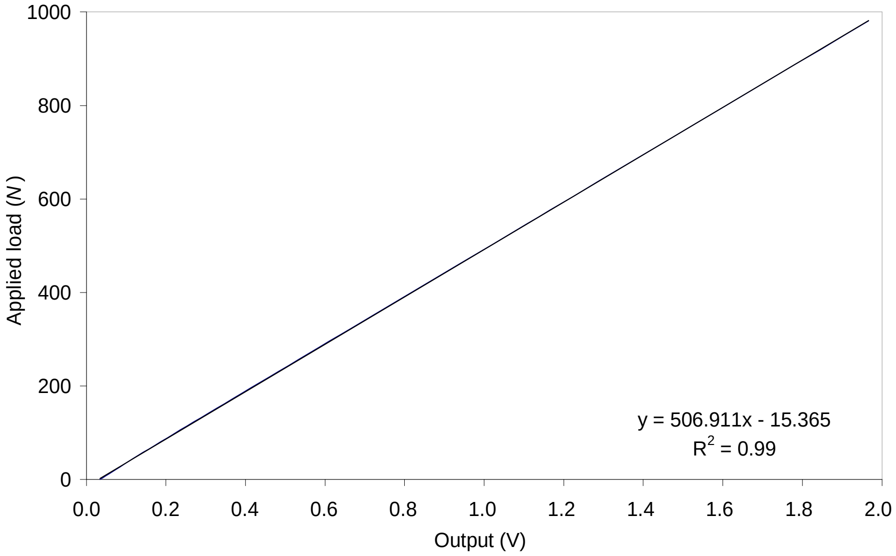


Figure A.3.6: Calibration curves for Instron 1122 (Instron, 1975) used during the compression tests for the measurement of fertiliser particle's strength.

APPENDIX CHAPTER 4

A.4.1 Calculated landing distances for biosolids granules, OMF_{10}, OMF_{15} and urea

i. Biosolids granules

Table A.4.1: Calculated landing distances based on the particle trajectory model for biosolids granules for increasing initial velocity and launch angle [h_0 =1 m].

$\rho_p = 1333\ (kg\ m^{-3})$	---------------------- Landing distance (m) -----------------------					
D_{50} =2.21 mm	α_0 **(degrees)**					
$v_0 (m\ s^{-1})$	**0**	**10**	**20**	**30**	**40**	**50**
5	1.80	2.01	2.14	2.17	2.09	1.89
10	3.18	3.73	4.06	4.15	4.00	3.62
15	4.29	5.14	5.59	5.67	5.41	4.85
20	5.23	6.31	6.81	6.84	6.48	5.77
25	6.03	7.31	7.83	7.80	7.34	6.50
30	6.74	8.16	8.69	8.60	8.05	7.10
35	7.36	8.90	9.42	9.28	8.66	7.61
40	7.91	9.55	10.05	9.86	9.17	8.04
45	8.40	10.12	10.60	10.38	9.62	8.42
50	8.85	10.63	11.10	10.83	10.02	8.75

Table A.4.2: Calculated landing distances based on the particle trajectory model for biosolids granules for increasing initial velocity and particle diameter [h_0 =1 m].

$\rho_p = 1333\ (kg\ m^{-3})$	----------------------------- Landing distance (m) ------------------------------									
$\alpha_0 = 0^\circ$	**Particle diameter (mm)**									
$v_0 (m\ s^{-1})$	**1.00**	**1.50**	**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**5.50**
5	1.27	1.58	1.75	1.86	1.93	1.98	2.02	2.05	2.07	2.09
10	2.04	2.67	3.06	3.32	3.51	3.65	3.75	3.84	3.91	3.96
15	2.61	3.50	4.10	4.52	4.84	5.08	5.28	5.43	5.55	5.64
20	3.06	4.18	4.96	5.55	6.00	6.35	6.61	6.82	7.00	7.14
25	3.43	4.74	5.70	6.44	7.00	7.44	7.78	8.06	8.29	8.49
30	3.74	5.23	6.35	7.22	7.88	8.40	8.82	9.17	9.46	9.72
35	4.02	5.66	6.92	7.90	8.66	9.26	9.76	10.17	10.53	10.85
40	4.27	6.05	7.43	8.50	9.35	10.04	10.61	11.09	11.52	11.89
45	4.49	6.40	7.88	9.04	9.98	10.74	11.38	11.94	12.42	12.86
50	4.70	6.71	8.29	9.54	10.55	11.39	12.10	12.72	13.26	13.75

ii. OMF$_{10}$

Table A.4.3: Calculated landing distances based on the particle trajectory model for OMF$_{10}$ for increasing initial velocity and launch angle [h_0 =1 m].

$\rho_p = 1297\ (kg\ m^{-3})$	Landing distance (m)					
D$_{50}$ =3.25 mm	α_0 **(degrees)**					
$v_0(m\ s^{-1})$	**0**	**10**	**20**	**30**	**40**	**50**
5	1.95	2.22	2.41	2.49	2.43	2.22
10	3.56	4.37	4.94	5.19	5.10	4.68
15	4.93	6.30	7.14	7.44	7.24	6.58
20	6.13	7.98	8.98	9.25	8.91	8.03
25	7.16	9.42	10.49	10.70	10.23	9.17
30	8.07	10.64	11.75	11.90	11.30	10.08
35	8.87	11.70	12.82	12.90	12.20	10.84
40	9.59	12.63	13.75	13.76	12.96	11.48
45	10.25	13.46	14.57	14.52	13.63	12.05
50	10.84	14.21	15.30	15.19	14.22	12.54

Table A.4.4: Calculated landing distances based on the particle trajectory model for OMF$_{10}$ for increasing initial velocity and particle diameter [h_0 =1 m].

$\rho_p = 1297\ (kg\ m^{-3})$	Landing distance (m)									
$\alpha_0 = 0^\circ$	**Particle diameter (mm)**									
$v_0(m\ s^{-1})$	**1.00**	**1.50**	**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**5.50**
5	1.25	1.57	1.74	1.85	1.92	1.97	2.01	2.04	2.07	2.09
10	2.01	2.64	3.03	3.30	3.49	3.63	3.73	3.82	3.89	3.95
15	2.56	3.46	4.06	4.48	4.80	5.05	5.24	5.40	5.52	5.62
20	3.00	4.11	4.90	5.49	5.94	6.29	6.56	6.78	6.95	7.10
25	3.36	4.66	5.63	6.36	6.93	7.37	7.72	8.00	8.23	8.44
30	3.67	5.14	6.26	7.12	7.79	8.32	8.74	9.09	9.39	9.65
35	3.94	5.56	6.82	7.79	8.55	9.16	9.66	10.08	10.44	10.76
40	4.18	5.94	7.31	8.38	9.23	9.92	10.49	10.98	11.41	11.79
45	4.40	6.28	7.75	8.91	9.85	10.61	11.25	11.81	12.30	12.73
50	4.60	6.59	8.15	9.40	10.41	11.24	11.95	12.57	13.12	13.61

iii. OMF$_{15}$

Table A.4.5: Calculated landing distances based on the particle trajectory model for OMF$_{15}$ for increasing initial velocity and launch angle [h_0 =1 m].

$\rho_p = 1357\ (kg\ m^{-3})$	---------------------- **Landing distance (m)** -----------------------					
D$_{50}$ =4.79 mm	α_0 **(degrees)**					
$v_0 (m\ s^{-1})$	**0**	**10**	**20**	**30**	**40**	**50**
5	2.07	2.39	2.64	2.77	2.74	2.52
10	3.89	5.01	5.89	6.38	6.40	5.95
15	5.52	7.59	9.06	9.74	9.69	8.94
20	6.96	9.93	11.78	12.52	12.31	11.27
25	8.24	11.99	14.07	14.77	14.40	13.09
30	9.39	13.80	16.01	16.66	16.11	14.57
35	10.45	15.41	17.68	18.24	17.55	15.80
40	11.42	16.84	19.14	19.62	18.78	16.85
45	12.31	18.13	20.44	20.83	19.86	17.75
50	13.13	19.29	21.60	21.90	20.82	18.55

Table A.4.6: Calculated landing distances based on the particle trajectory model for OMF$_{15}$ for increasing initial velocity and particle diameter [h_0 =1 m].

$\rho_p = 1357\ (kg\ m^{-3})$	----------------------------- **Landing distance (m)** ------------------------------									
$\alpha_0 = 0^\circ$	**Particle diameter (mm)**									
$v_0 (m\ s^{-1})$	**1.00**	**1.50**	**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**5.50**
5	1.28	1.59	1.76	1.87	1.94	1.99	2.02	2.05	2.07	2.09
10	2.07	2.69	3.08	3.34	3.52	3.66	3.76	3.85	3.92	3.97
15	2.64	3.53	4.13	4.55	4.86	5.11	5.30	5.45	5.57	5.66
20	3.09	4.22	5.00	5.59	6.03	6.38	6.64	6.85	7.02	7.17
25	3.47	4.79	5.75	6.49	7.05	7.48	7.82	8.10	8.33	8.53
30	3.79	5.29	6.41	7.28	7.94	8.46	8.87	9.22	9.51	9.77
35	4.08	5.73	6.99	7.96	8.72	9.33	9.82	10.24	10.59	10.91
40	4.33	6.12	7.50	8.58	9.43	10.11	10.68	11.16	11.59	11.96
45	4.56	6.47	7.96	9.13	10.06	10.83	11.47	12.02	12.50	12.94
50	4.77	6.79	8.38	9.63	10.65	11.48	12.19	12.81	13.36	13.84

i. Urea

Table A.4.7: Calculated landing distances based on the particle trajectory model for urea for increasing initial velocity and launch angle [h_0 =1 m].

$\rho_p = 1432\ (kg\ m^{-3})$	---------------------- Landing distance (m) -----------------------					
D50 =3.03 mm			α_0 **(degrees)**			
$v_0 (m\ s^{-1})$	**0**	**10**	**20**	**30**	**40**	**50**
5	1.95	2.22	2.42	2.50	2.44	2.23
10	3.57	4.39	4.97	5.23	5.14	4.71
15	4.95	6.34	7.20	7.51	7.31	6.64
20	6.16	8.05	9.07	9.35	9.01	8.13
25	7.22	9.52	10.63	10.85	10.37	9.30
30	8.15	10.78	11.92	12.07	11.47	10.23
35	8.97	11.87	13.02	13.10	12.39	11.01
40	9.70	12.83	13.98	13.99	13.18	11.68
45	10.37	13.68	14.82	14.77	13.87	12.25
50	10.99	14.45	15.57	15.46	14.48	12.76

Table A.4.8: Calculated landing distances based on the particle trajectory model for urea for increasing initial velocity and particle diameter [h_0 =1 m].

$\rho_p = 1432\ (kg\ m^{-3})$	----------------------------- Landing distance (m) ------------------------------									
$\alpha_0 = 0^\circ$					**Particle diameter (mm)**					
$v_0 (m\ s^{-1})$	**1.00**	**1.50**	**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**5.50**
5	1.31	1.62	1.78	1.88	1.95	2.00	2.03	2.06	2.08	2.10
10	2.13	2.75	3.13	3.39	3.56	3.70	3.80	3.88	3.94	4.00
15	2.73	3.63	4.22	4.63	4.94	5.17	5.36	5.51	5.62	5.71
20	3.21	4.34	5.12	5.70	6.14	6.48	6.74	6.94	7.10	7.24
25	3.60	4.94	5.90	6.64	7.19	7.62	7.95	8.22	8.44	8.64
30	3.94	5.46	6.59	7.45	8.11	8.62	9.03	9.37	9.66	9.91
35	4.24	5.92	7.20	8.17	8.93	9.52	10.01	10.42	10.77	11.09
40	4.51	6.33	7.73	8.81	9.66	10.34	10.90	11.38	11.80	12.17
45	4.75	6.71	8.21	9.39	10.32	11.08	11.72	12.27	12.75	13.18
50	4.97	7.04	8.65	9.91	10.93	11.77	12.47	13.09	13.63	14.12

Appendix A.4.2: Statistical analyses corresponding to Chapter 4: Fertiliser particle aerodynamics

The following analyses correspond to the spreading test conducted at the experimental site at Broxton (Cheshire) using a pneumatic fertiliser applicator.

A.4.2.1: Statistical analysis – spreading test

Table A.4.9: Analysis of variance for the fertiliser collected in the trays during the spreading test

Variate: Weight (g)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	35.529	17.764	6.7	
Block.*Units* stratum					
Position	8	18.126	2.266	0.85	**0.572**
Residual	16	42.454	2.653		
Total	26	96.108			

A.4.2.2: Regression analysis – spreading test

Response variate:	Weight
Fitted terms:	Constant, Position

Table A.4.10: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.84	0.839	0.22	**0.643**
Residual	25	95.27	3.811		
Total	26	96.11	3.696		

Residual variance exceeds variance of response variate.
Standard error of observations is estimated to be 1.95.

Table A.4.11: Estimates of parameters

Parameter	estimate	s.e.	t(25)	t pr.
Constant	11.027	0.819	13.47	**<.001**
Position	0.068	0.146	0.47	**0.643**

Appendix A.4.3: Particle trajectory model

The particle trajectory model can be found in the CD enclosed in the following folder:

- EngD Thesis\Appendices\Appendix Chapter 4 Fertiliser particle aerodynamics\Particle trajectory model.

In order to operate the programme, the steps indicated below need to be followed:

1. Open the folder “Ejecutable”,
2. Open the file “TiroParabolico.exe”,
3. Define “ambient temperature” (in degrees Celsius) and press “enter”; work with 15°C since the model has been programmed to use the density of the air corresponding to this temperature (i.e. 1.225 kg m^{-3}),
4. Define “launch speed” and press “enter”; i.e. the initial velocity of the particle at the instant it leaves the spinning disc and it is given in $m\ s^{-1}$; (v_0),
5. Define “launch angle” and press “enter”; i.e. the initial angle at which the particle is projected from the spinning disc and it is given in degrees; (α_0),
6. Define “particle radius” and press “enter”; i.e. the diameter of the particle in *mm* divided by 2,
7. Define “particle density” and press “enter”; this is expressed in kg m^{-3} (ρ_p),
8. Define “initial height above the ground” and press “enter”; this is given in *m* and it corresponds to the distance from the ground level to the edge of the spinning disc,
9. Define “C_D model” as follow:
    a. Enter 0 if working in “no drag” conditions, and press enter;
    b. Enter 1 if decided to calculate C_D according to Parkin et al. (2005), and press enter;
    c. Enter 2 if decided to calculate C_D according to Grift et al. (1997), and press enter.
10. The calculated landing distance; i.e. “flight distance” in *m*, should appear on the screen after a few seconds. A complete set of results can be found by opening the file “Results.txt” in the same “Ejecutable” folder. A summarised dataset can be found in “ShortResults.txt”, also in the same folder. The last two columns will show the trajectory of the particle in both “*x*” and “*y*” axes.

Appendix A.4.4: Relationship between the drag coefficient (C_D) and the Reynolds number (*Re*)

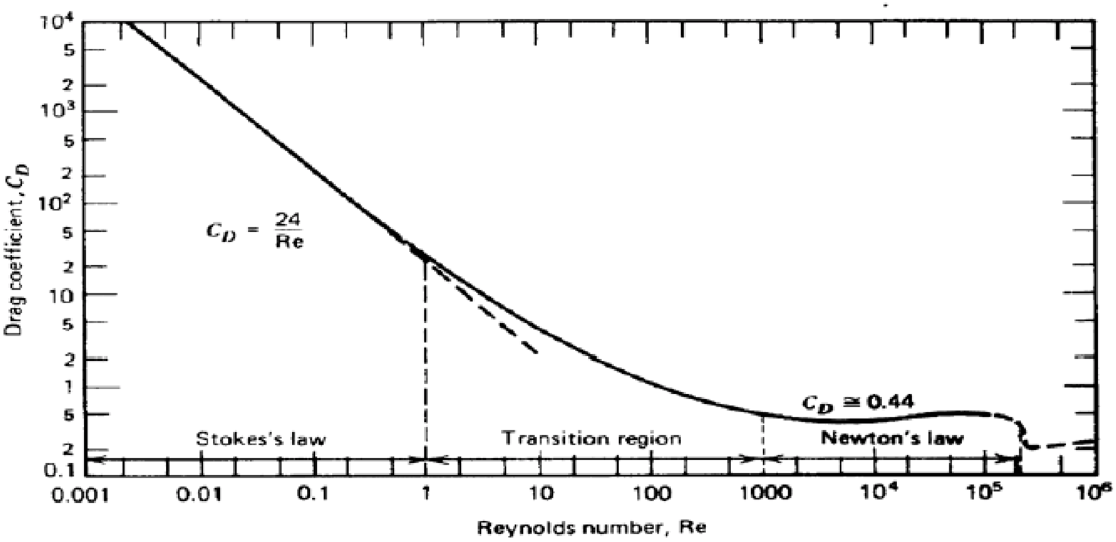


Figure A.4.1: Drag coefficient (C_D) as a function of the Reynolds number (*Re*) for spherical fertiliser particles (after: Parkin et al., 2005).

APPENDIX CHAPTER 5

Appendix A.5.1: Soil incubation studies – statistical analyses

i. Pilot investigation – nitrogen

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Box's tests for symmetry of the covariance matrix

Chi-square 265.64 on 13 degrees of freedom: probability 0.000

F-test 20.41 on 13 and 10326 degrees of freedom: probability 0.000

Greenhouse-Geisser epsilon

Epsilon =0.5893

Analysis of variance (repeated measure)

Variate: SMN T=0, SMN T=30, SMN T=60, SMN T=90, SMN T=120

Table A.5.1: Analysis of variance – soil mineral nitrogen (pilot investigation)

Variate: Soil mineral nitrogen (SMN) **Source of variation**	**(*)d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	19288	19288	16.53	**<.001**
Control_v_Treated	1	140666	140666	120.52	**<.001**
Soils.Control_v_Treated	1	1031	1031	0.88	**0.355**
Control_v_Treated.Treatment	1	9617	9617	8.24	**0.007**
Control_v_Treated.Rate	1	189521	189521	162.38	**<.001**
Soils.Control_v_Treated.Treatment	1	26	26	0.02	**0.882**
Soils.Control_v_Treated.Rate	1	1682	1682	1.44	**0.239**
Control_v_Treated.Treatment.Rate	1	0	0	0	**0.997**
Soils.Control_v_Treated.Treatment.Rate	1	92	92	0.08	**0.781**
Residual	30	35015	1167	0.83	
Subject.Time stratum					
d.f. correction factor 0.5893					
Time	4	616508	154127	109.41	**<.001**
Time.Soils	4	1796	449	0.32	**0.763**
Time.Control_v_Treated	4	44938	11235	7.97	**<.001**
Time.Soils.Control_v_Treated	4	837	209	0.15	**0.893**
Time.Control_v_Treated.Treatment	4	21106	5276	3.75	**0.022**
Time.Control_v_Treated.Rate	4	64564	16141	11.46	**<.001**
Time.Soils.Control_v_Treated.Treatment	4	11478	2870	2.04	**0.13**
Time.Soils.Control_v_Treated.Rate	4	5516	1379	0.98	**0.392**
Time.Control_v_Treated.Treatment.Rate	4	1614	403	0.29	**0.787**
Time.Soils.Control_v_Treated.Treatment.Rate	4	5342	1336	0.95	**0.405**
Residual	**120**	**169049**	**1409**		
Total	**199**	**1339686**			

(*)d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

ii. Nitrogen: first run

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Box's tests for symmetry of the covariance matrix

Chi-square 188.06 on 8 degrees of freedom: probability 0.000

F-test 23.49 on 8 and 12230 degrees of freedom: probability 0.000

Greenhouse-Geisser epsilon

Epsilon 0.9225

Analysis of variance (repeated measure)

Variate: SMN T=0, SMN T=30, SMN T=60, SMN T=90

Table A.5.2: Analysis of variance – soil mineral nitrogen (first run)

Variate: Soil mineral nitrogen (SMN) **Source of variation**	**(*)d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	24171.97	24171.97	75.8	**<.001**
Control_v_Treated	1	31001.23	31001.23	97.22	**<.001**
Soils.Control_v_Treated	1	741.54	741.54	2.33	**0.138**
Control_v_Treated.Treatment	1	9195.38	9195.38	28.84	**<.001**
Control_v_Treated.Rate	1	33809.75	33809.75	106.02	**<.001**
Soils.Control_v_Treated.Treatment	1	55.52	55.52	0.17	**0.679**
Soils.Control_v_Treated.Rate	1	3064.47	3064.47	9.61	**0.004**
Control_v_Treated.Treatment.Rate	1	5466.66	5466.66	17.14	**<.001**
Soils.Control_v_Treated.Treatment.Rate	1	428.15	428.15	1.34	**0.256**
Residual	30	9566.78	318.89	3.48	
Subject.Time stratum					
d.f. correction factor 0.9225					
Time	3	394272.86	131424.29	1433.38	**<.001**
Time.Soils	3	2795.25	931.75	10.16	**<.001**
Time.Control_v_Treated	3	10808.54	3602.85	39.29	**<.001**
Time.Soils.Control_v_Treated	3	398.57	132.86	1.45	**0.236**
Time.Control_v_Treated.Treatment	3	3666.65	1222.22	13.33	**<.001**
Time.Control_v_Treated.Rate	3	11692.02	3897.34	42.51	**<.001**
Time.Soils.Control_v_Treated.Treatment	3	476.89	158.96	1.73	**0.17**
Time.Soils.Control_v_Treated.Rate	3	1373.73	457.91	4.99	**0.004**
Time.Control_v_Treated.Treatment.Rate	3	2131.18	710.39	7.75	**<.001**
Time.Soils.Control_v_Treated.Treatment.Rate	3	212.48	70.83	0.77	**0.503**
Residual	**90**	**8251.96**	**91.69**		
Total	**159**	**553581.58**			

(*)d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

iii. Nitrogen: second run

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Box's tests for symmetry of the covariance matrix

Chi-square 191.40 on 8 degrees of freedom: probability 0.000

F-test 23.90 on 8 and 9906 degrees of freedom: probability 0.000

Greenhouse-Geisser epsilon

Epsilon 0.6313

Analysis of variance (repeated measure)

Variate: SMN T=0, SMN T=30, SMN T=60, SMN T=90

Table A.5.3: Analysis of variance – soil mineral nitrogen (second run)

Variate: Soil mineral nitrogen (SMN) **Source of variation**	**(*)d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	20117.1	20117.1	46.23	**<.001**
Control_v_Treated	1	49696.9	49696.9	114.19	**<.001**
Soils.Control_v_Treated	1	162.6	162.6	0.37	**0.546**
Control_v_Treated.Treatment	1	9636.8	9636.8	22.14	**<.001**
Control_v_Treated.Rate	1	31227.1	31227.1	71.75	**<.001**
Soils.Control_v_Treated.Treatment	1	384.9	384.9	0.88	**0.355**
Soils.Control_v_Treated.Rate	1	30.9	30.9	0.07	**0.792**
Control_v_Treated.Treatment.Rate	1	6672.7	6672.7	15.33	**<.001**
Soils.Control_v_Treated.Treatment.Rate	1	128.7	128.7	0.3	**0.591**
Residual	30	13055.9	435.2	2.02	
Subject.Time stratum					
d.f. correction factor 0.6313					
Time	3	419035.3	139678.4	649.07	**<.001**
Time.Soils	3	3293.6	1097.9	5.1	**0.01**
Time.Control_v_Treated	3	16648.1	5549.4	25.79	**<.001**
Time.Soils.Control_v_Treated	3	392.3	130.8	0.61	**0.54**
Time.Control_v_Treated.Treatment	3	3336.7	1112.2	5.17	**0.01**
Time.Control_v_Treated.Rate	3	11588.3	3862.8	17.95	**<.001**
Time.Soils.Control_v_Treated.Treatment	3	698	232.7	1.08	**0.344**
Time.Soils.Control_v_Treated.Rate	3	437.4	145.8	0.68	**0.504**
Time.Control_v_Treated.Treatment.Rate	3	2397.4	799.1	3.71	**0.033**
Time.Soils.Control_v_Treated.Treatment.Rate	3	160.5	53.5	0.25	**0.769**
Residual	**86**	**18507**	**215.2**		
Total	**155**	**601493.6**			

(*)d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

iv. Combined results (1st and 2nd runs) incubation studies – nitrogen

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Box's tests for symmetry of the covariance matrix

Chi-square 195.67 on 8 degrees of freedom: probability 0.000

F-test 24.44 on 8 and 11428 degrees of freedom: probability 0.000

Greenhouse-Geisser epsilon

Epsilon 0.7331

Analysis of variance (repeated measure)

Variate: SMN T=0, SMN T=30, SMN T=60, SMN T=90

Table A.5.4: Analysis of variance – soil mineral nitrogen (pilot investigation, 1st and 2nd runs)

Variate: Soil mineral nitrogen (SMN)

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	16742.4	16742.4	92.58	**<.001**
Control_v_Treated	1	60559.5	60559.5	334.86	**<.001**
Soils.Control_v_Treated	1	0.20	0.20	0.00	**0.972**
Control_v_Treated.Treatment	1	7555.3	7555.3	41.78	**<.001**
Control_v_Treated.Rate	1	61881.6	61881.6	342.17	**<.001**
Soils.Control_v_Treated.Treatment	1	104.4	104.4	0.58	**0.453**
Soils.Control_v_Treated.Rate	1	349.1	349.1	1.93	**0.175**
Control_v_Treated.Treatment.Rate	1	1400.5	1400.5	7.74	**0.009**
Soils.Control_v_Treated.Treatment.Rate	1	0.70	0.70	0.00	**0.952**
Residual	30	5425.5	180.9	1.27	
Subject.Time stratum					
d.f. correction factor 0.7331					
Time	3	453554.1	151184.7	1064.69	**<.001**
Time.Soils	3	420.1	140	0.99	**0.385**
Time.Control_v_Treated	3	20357	6785.7	47.79	**<.001**
Time.Soils.Control_v_Treated	3	118.2	39.4	0.28	**0.779**
Time.Control_v_Treated.Treatment	3	6765.5	2255.2	15.88	**<.001**
Time.Control_v_Treated.Rate	3	21019.7	7006.6	49.34	**<.001**
Time.Soils.Control_v_Treated.Treatment	3	2249.5	749.8	5.28	**0.006**
Time.Soils.Control_v_Treated.Rate	3	151.4	50.5	0.36	**0.722**
Time.Control_v_Treated.Treatment.Rate	3	494.2	164.7	1.16	**0.323**
Time.Soils.Control_v_Treated.Treatment.Rate	3	372.3	124.1	0.87	**0.431**
Residual	**89**	**12637.9**	**142.0**		
Total	**158**	**664832.2**			

(*)d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

v. Pilot investigation: total soil nitrogen

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Greenhouse-Geisser epsilon

Epsilon 1.000

Analysis of variance (repeated measure)

Variate: After; Before

Table A.5.5: Analysis of variance – total soil nitrogen (pilot investigation)

Variate: Total soil nitrogen (TN_{soil})					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	0.003861	0.00386123	84.54	**<.001**
Control_v_Treated	1	0.000286	0.00028623	6.27	**0.031**
Soils.Control_v_Treated	1	0.000005	0.00000490	0.11	**0.75**
Control_v_Treated.Treatment	1	0.000085	0.00008450	1.85	**0.204**
Control_v_Treated.Rate	1	0.000120	0.00012012	2.63	**0.136**
Soils.Control_v_Treated.Treatment	1	0.000078	0.00007812	1.71	**0.22**
Soils.Control_v_Treated.Rate	1	0.000221	0.00022050	4.83	**0.053**
Control_v_Treated.Treatment.Rate	1	0.000000	0.00000000	0.000	**1.000**
Soils.Control_v_Treated.Treatment.Rate	1	0.000021	0.00002113	0.460	**0.512**
Residual	10	0.000457	0.00004567	1.000	
Subject.Time stratum					
d.f. correction factor 1.0000					
Time	1	0.000801	0.00080102	17.54	**0.002**
Time.Soils	1	0.000007	0.00000723	0.16	**0.699**
Time.Control_v_Treated	1	0.000286	0.00028623	6.27	**0.031**
Time.Soils.Control_v_Treated	1	0.000005	0.00000490	0.11	**0.75**
Time.Control_v_Treated.Treatment	1	0.000085	0.00008450	1.85	**0.204**
Time.Control_v_Treated.Rate	1	0.000120	0.00012013	2.63	**0.136**
Time.Soils.Control_v_Treated.Treatment	1	0.000078	0.00007812	1.71	**0.22**
Time.Soils.Control_v_Treated.Rate	1	0.000221	0.00022050	4.83	**0.053**
Time.Control_v_Treated.Treatment.Rate	1	0.000000	0.00000000	0.000	**1.000**
Time.Soils.Control_v_Treated.Treatment.Rate	1	0.000021	0.00002113	0.46	**0.512**
Residual	10	0.000457	0.00004567		
Total	39	0.007214			

(*)d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

vi. Nitrogen: total soil nitrogen 1st and 2nd runs

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Greenhouse-Geisser epsilon

Epsilon 1.000

Analysis of variance (repeated measure)

Variate: After; Before

Table A.5.6: Analysis of variance – total soil nitrogen (1st and 2nd runs)

Variate: Total soil nitrogen (TN_{soil})					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Subject stratum					
Soils	1	0.015682	0.015682	268.830	**<.001**
Control_v_Treated	1	0.000167	0.000167	2.860000	**0.106**
Soils.Control_v_Treated	1	0.000027	0.000027	0.460000	**0.507**
Control_v_Treated.Treatment	1	0.000208	0.000208	3.570000	**0.073**
Control_v_Treated.Rate	1	0.000208	0.000208	3.570000	**0.073**
Soils.Control_v_Treated.Treatment	1	0.000208	0.000208	3.570000	**0.073**
Soils.Control_v_Treated.Rate	1	0.000008	0.000008	0.140000	**0.709**
Control_v_Treated.Treatment.Rate	1	0.000000	0.000000	0.000000	**1.000**
Soils.Control_v_Treated.Treatment.Rate	1	0.000033	0.000033	0.570000	**0.459**
Residual	20	0.001167	0.000058	1.210000	
Subject.Time stratum					
d.f. correction factor 1.0000					
Time	1	0.005042	0.005042	104.310	**<.001**
Time.Soils	1	0.000282	0.000282	5.830000	**0.025**
Time.Control_v_Treated	1	0.000167	0.000167	3.450000	**0.078**
Time.Soils.Control_v_Treated	1	0.000027	0.000027	0.550000	**0.466**
Time.Control_v_Treated.Treatment	1	0.000208	0.000208	4.310000	**0.051**
Time.Control_v_Treated.Rate	1	0.000208	0.000208	4.310000	**0.051**
Time.Soils.Control_v_Treated.Treatment	1	0.000208	0.000208	4.310000	**0.051**
Time.Soils.Control_v_Treated.Rate	1	0.000008	0.000008	0.170000	**0.682**
Time.Control_v_Treated.Treatment.Rate	1	0.000000	0.000000	0.000000	**1.000**
Time.Soils.Control_v_Treated.Treatment.Rate	1	0.000033	0.000033	0.690000	**0.416**
Residual	**20**	**0.000967**	**0.000048**		
Total	**59**	**0.024858**			

(*)d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

APPENDIX A.5.2: Soil incubation studies – statistical analyses

i. Phosphorus (mg kg^{-1})

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Box's tests for symmetry of the covariance matrix

Chi-square 13.39 on 8 degrees of freedom: probability 0.099

F-test 1.67 on 8 and 1957 degrees of freedom: probability 0.102

Greenhouse-Geisser epsilon

Epsilon =0.8477

Analysis of variance (repeated measure)

Variate: Ext P T=0, Ext P T=30, Ext P T=60, Ext P T=90

Table A.5.7: Analysis of variance – soil extractable phosphorus (mg kg^{-1})

Variate: Soil extractable phosphorus (mg kg^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Subject stratum					
Soils	1	1349.968	1349.968	157.76	**<.001**
Control_v_Treated	1	555.426	555.426	64.91	**<.001**
Soils.Control_v_Treated	1	29.091	29.091	3.40	**0.075**
Control_v_Treated.Treatment	1	2373.189	2373.189	277.34	**<.001**
Control_v_Treated.Rate	1	418.227	418.227	48.88	**<.001**
Soils.Control_v_Treated.Treatment	1	133.112	133.112	15.56	**<.001**
Soils.Control_v_Treated.Rate	1	7.368	7.368	0.86	**0.361**
Control_v_Treated.Treatment.Rate	1	240.181	240.181	28.07	**<.001**
Soils.Control_v_Treated.Treatment.Rate	1	7.395	7.395	0.86	**0.36**
Residual	30	256.705	8.557	1.79	
Subject.Time stratum					
d.f. correction factor 0.8477					
Time	3	2831.07	943.69	197.05	**<.001**
Time.Soils	3	43.957	14.652	3.06	**0.044**
Time.Control_v_Treated	3	188.728	62.909	13.14	**<.001**
Time.Soils.Control_v_Treated	3	11.193	3.731	0.78	**0.492**
Time.Control_v_Treated.Treatment	3	800.667	266.889	55.73	**<.001**
Time.Control_v_Treated.Rate	3	155.748	51.916	10.84	**<.001**
Time.Soils.Control_v_Treated.Treatment	3	49.191	16.397	3.42	**0.03**
Time.Soils.Control_v_Treated.Rate	3	11.423	3.808	0.8	**0.484**
Time.Control_v_Treated.Treatment.Rate	3	85.509	28.503	5.95	**0.002**
Time.Soils.Control_v_Treated.Treatment.Rate	3	6.284	2.095	0.44	**0.695**
Residual	**63**	**301.717**	**4.789**		
Total	**132**	**7897.907**			

$^{(*)}$d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

ii. Phosphorus (mg l^{-1})

Treatment structure:

Soils*Control_v_Treated/ (Treatment*Rate)

Box's tests for symmetry of the covariance matrix

Chi-square 14.31 on 8 degrees of freedom: probability 0.074

F-test 1.78 on 8 and 1957 degrees of freedom: probability 0.076

Greenhouse-Geisser epsilon

Epsilon =0.8437

Analysis of variance (repeated measure)

Variate: Ext P T=0, Ext P T=30, Ext P T=60, Ext P T=90

Table A.5.8: Analysis of variance – soil extractable phosphorus (mg l^{-1})

Variate: Soil extractable phosphorus (mg l^{-1}) **Source of variation**	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	258.341	258.341	17.22	**<.001**
Control_v_Treated	1	934.275	934.275	62.28	**<.001**
Soils.Control_v_Treated	1	69.834	69.834	4.66	**0.039**
Control_v_Treated.Treatment	1	3970.383	3970.383	264.66	**<.001**
Control_v_Treated.Rate	1	677.948	677.948	45.19	**<.001**
Soils.Control_v_Treated.Treatment	1	310.927	310.927	20.73	**<.001**
Soils.Control_v_Treated.Rate	1	4.665	4.665	0.31	**0.581**
Control_v_Treated.Treatment.Rate	1	402.138	402.138	26.81	**<.001**
Soils.Control_v_Treated.Treatment.Rate	1	19.736	19.736	1.32	**0.260**
Residual	30	450.047	15.002	1.9	
Subject.Time stratum					
d.f. correction factor 0.8437					
Time	3	4692.121	1564.04	197.67	**<.001**
Time.Soils	3	136.649	45.55	5.76	**0.003**
Time.Control_v_Treated	3	316.928	105.643	13.35	**<.001**
Time.Soils.Control_v_Treated	3	25.637	8.546	1.08	**0.358**
Time.Control_v_Treated.Treatment	3	1340.347	446.782	56.47	**<.001**
Time.Control_v_Treated.Rate	3	253.504	84.501	10.68	**<.001**
Time.Soils.Control_v_Treated.Treatment	3	112.634	37.545	4.75	**0.008**
Time.Soils.Control_v_Treated.Rate	3	15.752	5.251	0.66	**0.553**
Time.Control_v_Treated.Treatment.Rate	3	143.78	47.927	6.06	**0.002**
Time.Soils.Control_v_Treated.Treatment.Rate	3	13.414	4.471	0.57	**0.612**
Residual	**63**	**498.47**	**7.912**		
Total	**132**	**10426.63**			

(*)d.f. are multiplied by the correction factors before calculating F probabilities.

Information summary

All terms orthogonal, none aliased.

APPENDIX A.5.3: Soil incubation studies – records soil extractable P

Table A.5.9: Values of soil extractable P (Olsen's-P) corresponding to the incubation trial for the study of phosphorus release characteristics of OMF_{15} expressed in mg [P] kg^{-1} and mg [P] l^{-1} (Soil bulk densities of 1.2 and 1.34 t m^{-3} for the clay loam and the sandy loam soils respectively; R_1 =150 kg [P_2O_5] ha^{-1}, R_2 =300 kg [P_2O_5] ha^{-1}; T= incubation time in days; SSP: single super-phosphate; n=4 except initial level n=3).

			mg [P] kg^{-1}			mg [P] l^{-1}		
Soil type	**P-rate (kg [P_2O_5] ha^{-1})**	**Treatment**	**Ext-P T=30**	**Ext-P T=60**	**Ext-P T=90**	**Ext-P T=30**	**Ext-P T=60**	**Ext-P T=90**
Clay loam	-	Initial level (T=0)	------------ 79.9 ------------			------------ 97.5 ------------		
Clay loam	Control	Control	84.5	84.9	84.2	103.1	103.5	102.7
Clay loam	Control	Control	85.6	84.9	86.4	104.5	103.5	105.5
Clay loam	Control	Control	83.3	83.3	-	101.6	101.6	-
Clay loam	Control	Control	82.4	-	86.6	100.5	-	105.7
Clay loam	150	SSP	-	-	86.4	-	-	105.5
Clay loam	150	SSP	90.2	90.3	91.1	110.0	110.1	111.1
Clay loam	150	SSP	90.8	88.9	-	110.8	108.5	-
Clay loam	150	SSP	91.5	87.2	91.2	111.6	106.4	111.3
Clay loam	300	SSP	96.1	-	101.5	117.2	-	123.8
Clay loam	300	SSP	-	98.9	94.4	-	120.6	115.2
Clay loam	300	SSP	99.9	96.8	98.6	121.9	118.1	120.3
Clay loam	300	SSP	98.6	97.9	97.9	120.3	119.5	119.5
Clay loam	150	OMF_{15}	87.4	82.1	85.3	106.6	100.2	104.1
Clay loam	150	OMF_{15}	84.9	82.3	82.6	103.6	100.4	100.8
Clay loam	150	OMF_{15}	83.1	83.3	-	101.4	101.6	-
Clay loam	150	OMF_{15}	81.5	83.1	85.3	99.4	101.4	104.1
Clay loam	300	OMF_{15}	88.2	91.4	84.1	107.6	111.5	102.5
Clay loam	300	OMF_{15}	-	83.7	87.9	-	102.2	107.2
Clay loam	300	OMF_{15}	83.9	83.3	87.9	102.4	101.6	107.2
Clay loam	300	OMF_{15}	86.1	88.2	85.0	105.0	107.6	103.7
Sandy loam	-	Initial level (T=0)	------------ 72.4 ------------			------------ 96.9 ------------		
Sandy loam	Control	Control	77.8	78.2	78.5	104.28	104.72	105.15
Sandy loam	Control	Control	77.8	78.2	78.5	104.28	104.72	105.15
Sandy loam	Control	Control	72.6	72.9	73.2	97.22	97.63	98.03
Sandy loam	Control	Control	80.2	78.4	78.7	107.49	105.06	105.50
Sandy loam	150	SSP	86.4	-	-	115.78	-	-
Sandy loam	150	SSP	86.9	84.2	85.2	116.45	112.84	114.11
Sandy loam	150	SSP	86.1	80.4	86.4	115.37	107.71	115.83
Sandy loam	150	SSP	-	93.5	-	-	125.25	-
Sandy loam	300	SSP	97.1	97.6	96.0	130.17	130.78	128.67
Sandy loam	300	SSP	93.5	90.3	-	125.25	121.00	-
Sandy loam	300	SSP	95.2	-	96.2	127.57	-	128.91
Sandy loam	300	SSP	-	100.0	97.0	-	134.00	129.95
Sandy loam	150	OMF_{15}	-	73.7	76.9	-	98.72	102.99
Sandy loam	150	OMF_{15}	76.1	83.6	-	101.97	111.98	-
Sandy loam	150	OMF_{15}	75.8	78.8	78.9	101.57	105.57	105.78
Sandy loam	150	OMF_{15}	76.1	-	77.5	101.97	-	103.85
Sandy loam	300	OMF_{15}	-	-	76.2	-	-	102.15
Sandy loam	300	OMF_{15}	77.9	78.4	78.1	104.39	105.08	104.71
Sandy loam	300	OMF_{15}	78.0	78.5	75.4	104.52	105.22	101.08
Sandy loam	300	OMF_{15}	77.4	77.9	-	103.72	104.40	-

APPENDIX CHAPTER 6

Appendix A.6.1: Description of the glasshouse facility at Cranfield University

As highlighted in **Section 6.2.1**, the experiment was initiated in April 2007 in the glasshouse facility at Silsoe Campus. In February 2008, following the closure of Silsoe, the experiment was re-located at a newly developed facility at Cranfield Campus (**Figure A.6.1**). It comprises three contiguous sections and it has an east-west orientation.

Figure A.6.1: Overview of the glasshouse facility at Cranfield University (top), close-up of the shade-cloth running on the horizontal frame along the roof (bottom-left) and close-up of a fan (bottom-right).

Anwyl (2008) acknowledged that glasshouses orientated in the east-west direction favour higher overall illumination and thermal efficiency whereas those in the north-south direction provide even light exposure throughout the year. Following the re-location of the experiment, the pots were first placed in the middle section and on a bench adjacent to the wall on the south-side of this wing. This location was found to be inconvenient since the frame of the glasshouse shaded some of the pots along the bench and provided uneven sunlight exposure. Therefore, a decision was made to transfer the pots on to the section located on the south side of the glasshouse and to use the middle bench instead of the laterals. This place offered a better and more even sunlight exposure compared with the original location.

An important aspect concerning the design of a glasshouse is with regards to its ventilation which is particularly important during the summer time. The glasshouse at Cranfield only offers ventilation through the roof with no ventilation on the side-walls. Therefore, the intake of air and its circulation from the bottom to the top of the glasshouse to help evacuate the hot air inside is restricted by its design and affected cooling in the summer. Shading is also possible by means of a sliding shade-cloth that moves across on the horizontal frame of the glasshouse, beneath the roof. Its use did not provide a satisfactory solution because, when it was fully displayed, it completely sealed the roof overheating the glasshouse. Fans are also installed but they were placed at approximately 3 m height for which their efficiency in reducing the heat is limited. Based on the experience in the use of this facility, it is possible to formulate the following recommendations which are believed to be relatively inexpensive and could significantly improve its overall functioning:

- If possible, to provide side-ventilation; for example, by means of removable glass/PVC panels on the side-walls,
- To re-install the fans at a lower height to be able to simulate the effect of natural side-ventilation and enhance the evacuation of hot air inside,
- To use a permeable shade-cloth to allow shading but without affecting the ventilation on the roof – avoid sealing, and
- To re-arrange the position of the benches in the middle section to reduce the effect of shading from the glasshouse’s frame.

Appendix A.6.2: Records of fertiliser applications – glasshouse studies

Tables A.6.1-3 show the amounts of P_2O_5 and K_2O added annually on each individual pot according to the nitrogen rates and the fertiliser types used in the glasshouse experiment between 2007 and 2009. The differences recorded in the amount of P_2O_5 and K_2O year on year were due to differences in the nutrients' concentration encountered in the various fertiliser batches produced.

Table A.6.1: Amounts of P_2O_5 and K_2O applied to each pot with the fertilisers in 2007.

2007	**Treatment**					
Equivalent	**Biosolids**		**OMF$_{10}$**		**OMF$_{15}$**	
rate (kg [N] ha^{-1})	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]
0	-	-	-	-	-	-
150	1.19	0.03	0.45	0.26	0.34	0.19
300	2.38	0.06	0.90	0.51	0.67	0.37

Table A.6.2: Amounts of P_2O_5 and K_2O applied to each pot with the fertilisers in 2008.

2008	**Treatment**					
Equivalent	**Biosolids**		**OMF$_{10}$**		**OMF$_{15}$**	
rate (kg [N] ha^{-1})	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]
0	-	-	-	-	-	-
150	1.17	0.05	0.33	0.30	0.20	0.21
300	2.34	0.10	0.67	0.60	0.40	0.43

Table A.6.3: Amounts of P_2O_5 and K_2O applied to each pot with the fertilisers in 2009.

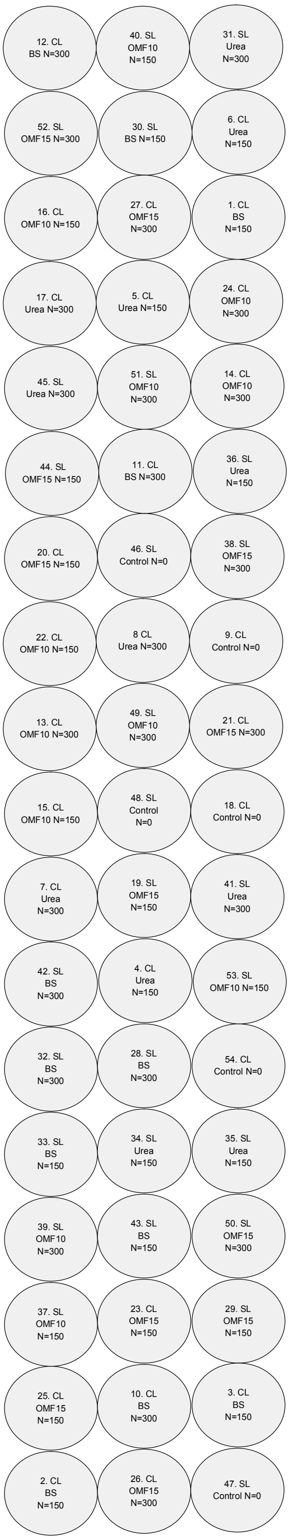
2009	**Treatment**					
Equivalent	**Biosolids**		**OMF$_{10}$**		**OMF$_{15}$**	
rate (kg [N] ha^{-1})	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]
0	-	-	-	-	-	-
150	1.47	0.02	0.46	0.29	0.26	0.26
300	2.95	0.04	0.92	0.58	0.52	0.51

Appendix A.6.3: Pots' arrangement – glasshouse studies

Notation:

- CL: Clay loam
- SL: Sandy loam
- BS: Biosolids
- N: nitrogen application rate (kg [N] ha^{-1}).

➡ N



12. CL BS N=300	40. SL OMF10 N=150	31. SL Urea N=300
52. SL OMF15 N=300	30. SL BS N=150	6. CL Urea N=150
16. CL OMF10 N=150	27. CL OMF15 N=300	1. CL BS N=150
17. CL Urea N=300	5. CL Urea N=150	24. CL OMF10 N=300
45. SL Urea N=300	51. SL OMF10 N=300	14. CL OMF10 N=300
44. SL OMF15 N=150	11. CL BS N=300	36. SL Urea N=150
20. CL OMF15 N=150	46. SL Control N=0	38. SL OMF15 N=300
22. CL OMF10 N=150	8 CL Urea N=300	9. CL Control N=0
13. CL OMF10 N=300	49. SL OMF10 N=300	21. CL OMF15 N=300
15. CL OMF10 N=150	48. SL Control N=0	18. CL Control N=0
7. CL Urea N=300	19. SL OMF15 N=150	41. SL Urea N=300
42. SL BS N=300	4. CL Urea N=150	53. SL OMF10 N=150
32. SL BS N=300	28. SL BS N=300	54. CL Control N=0
33. SL BS N=150	34. SL Urea N=150	35. SL Urea N=150
39. SL OMF10 N=300	43. SL BS N=150	50. SL OMF15 N=300
37. SL OMF10 N=150	23. CL OMF15 N=150	29. SL OMF15 N=150
25. CL OMF15 N=150	10. CL BS N=300	3. CL BS N=150
2. CL BS N=150	26. CL OMF15 N=300	47. SL Control N=0

Figure A.6.2: Pots' arrangement in the glasshouse showing the pot number, the soil type, and the treatment; i.e. fertiliser type and nitrogen application rate.

Appendix A.6.4: Glasshouse studies – statistical analyses

A.6.4.1 Statistical analysis – annual dry matter yield of rye grass

Table A.6.4: Analysis of variance of annual dry matter yield – rye grass 2007

Variate: Annual yield 2007 - Grass

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Soils	1	12310093	12310093	259.36	**<.001**
Control_v_Treated	1	83054312	83054312	1749.88	**<.001**
Soils.Control_v_Treated	1	388347	388347	8.18	**0.007**
Control_v_Treated.Fertiliser	3	63653788	21217929	447.04	**<.001**
Control_v_Treated.Rate	1	84629325	84629325	1783.07	**<.001**
Soils.Control_v_Treated.Fertiliser	3	548128	182709	3.85	**0.018**
Soils.Control_v_Treated.Rate	1	75640	75640	1.59	**0.215**
Control_v_Treated.Fertiliser.Rate	3	10520663	3506888	73.89	**<.001**
Soils.Control_v_Treated.Fertiliser.Rate	3	765361	255120	5.38	**0.004**
Residual	**35**	**1661196**	**47463**		
Total	**52**	**2.56336486**			

Table A.6.5: Analysis of variance of annual dry matter yield – rye grass 2008

Variate: Annual yield 2008 - Grass

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Soils	1	15281	15281	0.05	**0.823**
Control_v_Treated	1	32959885	32959885	109.51	**<.001**
Soils.Control_v_Treated	1	72782	72782	0.24	**0.626**
Control_v_Treated.Fertiliser	3	5368697	1789566	5.95	**0.002**
Control_v_Treated.Rate	1	13956329	13956329	46.37	**<.001**
Soils.Control_v_Treated.Fertiliser	3	3375125	1125042	3.74	**0.019**
Soils.Control_v_Treated.Rate	1	57374	57374	0.19	**0.665**
Control_v_Treated.Fertiliser.Rate	3	1744684	581561	1.93	**0.142**
Soils.Control_v_Treated.Fertiliser.Rate	3	1470652	490217	1.63	**0.2**
Residual	**36**	**10835513**	**300986**		
Total	**53**	**69856324**			

Table A.6.6: Analysis of variance of annual dry matter yield – rye grass 2009

Variate: Annual yield 2009 - Grass

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Soils	1	214818	214818	1.04	**0.315**
Control_v_Treated	1	23265797	23265797	112.39	**<.001**
Soils.Control_v_Treated	1	65564	65564	0.32	**0.577**
Control_v_Treated.Fertiliser	3	612089	204030	0.99	**0.41**
Control_v_Treated.Rate	1	16527339	16527339	79.84	**<.001**
Soils.Control_v_Treated.Fertiliser	3	427871	142624	0.69	**0.565**
Soils.Control_v_Treated.Rate	1	107503	107503	0.52	**0.476**
Control_v_Treated.Fertiliser.Rate	3	631623	210541	1.02	**0.396**
Soils.Control_v_Treated.Fertiliser.Rate	3	194252	64751	0.31	**0.816**
Residual	**36**	**7452424**	**207012**		
Total	**53**	**49499280**			

A.6.4.2 Statistical analysis – repeated measurement of analysis of variance of annual dry matter yield of rye grass 2007 – 2009

Table A.6.7: Repeated measurement of analysis of variance of annual dry matter yield – rye grass 2007-2009

Variate: Year 1,Year 2,Year 3

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	5231642	5231642	33.79	**<.001**
Control_v_Treated	1	1.3E+08	129599630	837.02	**<.001**
Soils.Control_v_Treated	1	118749	118749	0.77	**0.387**
Control_v_Treated.Fertiliser	3	37652854	12550951	81.06	**<.001**
Control_v_Treated.Rate	1	94983866	94983866	613.46	**<.001**
Soils.Control_v_Treated.Fertiliser	3	1199823	399941	2.58	**0.068**
Soils.Control_v_Treated.Rate	1	56715	56715	0.37	**0.549**
Control_v_Treated.Fertiliser.Rate	3	1247941	415980	2.69	**0.061**
Soils.Control_v_Treated.Fertiliser.Rate	3	427934	142645	0.92	**0.44**
Residual	36	5574032	154834	0.75	
Subject: Time stratum					
d.f. correction factor 0.7895					
Time	2	55481539	27740770	134.62	**<.001**
Time.Soils	2	8116005	4058002	19.69	**<.001**
Time.Control_v_Treated	2	10411712	5205856	25.26	**<.001**
Time.Soils.Control_v_Treated	2	359647	179824	0.87	**0.401**
Time.Control_v_Treated.Fertiliser	6	30966375	5161063	25.05	**<.001**
Time.Control_v_Treated.Rate	2	17933660	8966830	43.51	**<.001**
Time.Soils.Control_v_Treated.Fertiliser	6	3072458	512076	2.49	**0.045**
Time.Soils.Control_v_Treated.Rate	2	132161	66081	0.32	**0.675**
Time.Control_v_Treated.Fertiliser.Rate	6	11923676	1987279	9.64	**<.001**
Time.Soils.Control_v_Treated.Fertiliser.Rate	6	1938084	323014	1.57	**0.187**
Residual	**72**	**14836750**	**206066**		
Total	**161**	**431265255**			

(d.f. are multiplied by the correction factors before calculating F probabilities)

A.6.4.2 Statistical analysis – repeated measurement of analysis of variance of dry matter yield for individual cuts – rye grass 2007-2009

Table A.6.8: Repeated measurement of analysis of variance of dry matter yield for individual cuts – rye grass 2007-2009

**Variate: Cut 1,Cut 2,Cut 3,Cut 4,Cut 5,
Cut 6,Cut 7,Cut 8,Cut 9**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Subject stratum					
Soils	1	1743917	1743917	33.79	**<.001**
Control_v_Treated	1	43199982	43199982	837	**<.001**
Soils.Control_v_Treated	1	39593	39593	0.77	**0.387**
Control_v_Treated.Fertiliser	3	12551037	4183679	81.06	**<.001**
Control_v_Treated.Rate	1	31661451	31661451	613.44	**<.001**
Soils.Control_v_Treated.Fertiliser	3	399881	133294	2.58	**0.068**
Soils.Control_v_Treated.Rate	1	18917	18917	0.37	**0.549**
Control_v_Treated.Fertiliser.Rate	3	415964	138655	2.69	**0.061**
Soils.Control_v_Treated.Fertiliser.Rate	3	142665	47555	0.92	**0.440**
Residual	**36**	**1858073**	**51613**	**0.65**	
Subject: Time stratum					
d.f. correction factor 0.4533					
Time	8	379286909	47410864	599.19	**<.001**
Time.Soils	8	3665725	458216	5.79	**<.001**
Time.Control_v_Treated	8	23369685	2921211	36.92	**<.001**
Time.Soils.Control_v_Treated	8	467760	58470	0.74	**0.555**
Time.Control_v_Treated.Fertiliser	24	23202491	966770	12.22	**<.001**
Time.Control_v_Treated.Rate	8	16362678	2045335	25.85	**<.001**
Time.Soils.Control_v_Treated.Fertiliser	24	3748865	156203	1.97	**0.036**
Time.Soils.Control_v_Treated.Rate	8	887440	110930	1.4	**0.240**
Time.Control_v_Treated.Fertiliser.Rate	24	7457124	310714	3.93	**<.001**
Time.Soils.Control_v_Treated.Fertiliser.Rate	24	4238103	176588	2.23	**0.017**
Residual	**288**	**22788079**	**79125**		
Total	**485**	**577506341**			

(d.f. are multiplied by the correction factors before calculating F probabilities)

A.6.4.3 Regression analysis – Response of rye grass to the application of biosolids – Clay loam soil 2007

Regression analysis – quadratic model

Response variate: Annual Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.9: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	14603372	7301686	357.89	**<.001**
Residual	6	122411	20402		
Total	8	14725784	1840723		

Percentage variance accounted for 98.9

Standard error of observations is estimated to be 143.

Table A.6.10: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713.1	82.5	45.03	**<.001**
N_Rate.Fertiliser Biosolids	7.56	1.4	5.39	**0.002**
N_Rate_Sq.Fertiliser Biosolids	0.00936	0.00449	2.08	**0.082**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.11: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	14514682	14514682	481.3	**<.001**
Residual	7	211102	30157		
Total	8	14725784	1840723		
Change	1	88691	88691	4.35	**0.082**

Percentage variance accounted for 98.4

Standard error of observations is estimated to be 174

Table A.6.12: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3642.9	91.5	39.8	**<.001**
N_Rate.Fertiliser Biosolids	10.369	0.473	21.94	**<.001**

A.6.4.4 Regression analysis – Response of rye grass to the application of OMF_{10} – Clay loam soil 2007

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.13: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	27285777	13642888	145.15	**<.001**
Residual	6	563951	93992		
Total	8	27849728	3481216		

Percentage variance accounted for 97.3

Standard error of observations is estimated to be 307.

Table A.6.14: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	177	20.98	**<.001**
N_Rate.Fertiliser OMF_{10}	11.82	3.01	3.93	**0.008**
N_Rate_Sq.Fertiliser OMF_{10}	0.00795	0.00963	0.82	**0.441**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.15: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	27221826	27221826	303.48	**<.001**
Residual	7	627902	89700		
Total	8	27849728	3481216		
Change	1	63951	63951	0.68	**0.441**

Percentage variance accounted for 97.4

Standard error of observations is estimated to be 300.

Table A.6.16: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3654	158	23.15	**<.001**
N_Rate.Fertiliser OMF_{10}	14.2	0.815	17.42	**<.001**

A.6.4.4 Regression analysis – Response of rye grass to the application of OMF_{15} – Clay loam soil 2007

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.7.17: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	38904722	19452361	406.96	**<.001**
Residual	6	286795	47799		
Total	8	39191517	4898940		

Percentage variance accounted for 99.0

Standard error of observations is estimated to be 219.

Table A.6.18: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	126	29.42	**<.001**
N_Rate.Fertiliser OMF_{15}	19.73	2.15	9.2	**<.001**
N_Rate_Sq.Fertiliser OMF_{15}	-0.00923	0.00687	-1.34	**0.228**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.19: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	38818388	38818388	728.24	**<.001**
Residual	7	373128	53304		
Total	8	39191517	4898940		
Change	1	86334	86334	1.81	**0.228**

Percentage variance accounted for 98.9

Standard error of observations is estimated to be 231.

Table A.6.20: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3782	122	31.08	**<.001**
N_Rate.Fertiliser OMF_{15}	16.957	0.628	26.99	**<.001**

A.6.4.5 Regression analysis – Response of rye grass to the application of urea – Clay loam soil 2007

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.21: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	89654534	44827267	606.48	**<.001**
Residual	6	443485	73914		
Total	8	90098019	11262252		

Percentage variance accounted for 99.3

Standard error of observations is estimated to be 272.

Table A.6.22: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	157	23.66	**<.001**
N_Rate.Fertiliser Urea	20.48	2.67	7.68	**<.001**
N_Rate_Sq.Fertiliser Urea	0.01748	0.00854	2.05	**0.087**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.23: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	89345112	89345112	830.67	**<.001**
Residual	7	752908	107558		
Total	8	90098019	11262252		
Change	1	309422	309422	4.19	**0.087**

Percentage variance accounted for 99.0

Standard error of observations is estimated to be 328.

Table A.6.24: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3582	173	20.72	**<.001**
N_Rate.Fertiliser Urea	25.726	0.893	28.82	**<.001**

A.6.4.6 Regression analysis – Response of rye grass to the application of biosolids – Clay loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.25: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	6573076	3286538	17.01	**0.003**
Residual	6	1159547	193258		
Total	8	7732623	966578		

Percentage variance accounted for 80.0

Standard error of observations is estimated to be 440.

Table A.6.26: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3700	254	14.58	**<.001**
N_Rate.Fertiliser Biosolids	6.84	4.31	1.59	**0.164**
N_Rate_Sq.Fertiliser Biosolids	0.0005	0.0138	0.03	**0.974**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.27: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	6572857	6572857	39.67	**<.001**
Residual	7	1159766	165681		
Total	8	7732623	966578		
Change	1	218	218	0	**0.974**

Percentage variance accounted for 82.9

Standard error of observations is estimated to be 407

Table A.6.28: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3697	215	17.23	**<.001**
N_Rate.Fertiliser Biosolids	6.98	1.11	6.3	**<.001**

A.6.4.7 Regression analysis – Response of rye grass to the application of OMF_{10} – Clay loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.29: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	12954781	6477391	19.18	**0.002**
Residual	6	2026045	337674		
Total	8	14980827	1872603		

Percentage variance accounted for 82.0

Standard error of observations is estimated to be 581.

Table A.6.30: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	335	11.07	**<.001**
N_Rate.Fertiliser OMF_{10}	12.35	5.7	2.17	**0.074**
N_Rate_Sq.Fertiliser OMF_{10}	-0.0086	0.0183	-0.47	**0.655**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.31: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	12879987	12879987	42.92	**<.001**
Residual	7	2100840	300120		
Total	8	14980827	1872603		
Change	1	74794	74794	0.22	**0.655**

Percentage variance accounted for 84.0

Standard error of observations is estimated to be 548.

Table A.6.32: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3778	289	13.08	**<.001**
N_Rate.Fertiliser OMF_{10}	9.77	1.49	6.55	**<.001**

A.6.4.8 Regression analysis – Response of rye grass to the application of OMF_{15} – Clay loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.33: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	14001006	7000503	63.28	**<.001**
Residual	6	663782	110630		
Total	8	14664788	1833098		

Percentage variance accounted for 94.0

Standard error of observations is estimated to be 333

Table A.6.34: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	192	19.34	**<.001**
N_Rate.Fertiliser OMF_{15}	11.47	3.26	3.51	**0.013**
N_Rate_Sq.Fertiliser OMF_{15}	-0.0043	0.0105	-0.41	**0.694**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.35: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	13982129	13982129	143.37	**<.001**
Residual	7	682658	97523		
Total	8	14664788	1833098		
Change	1	18876	18876	0.17	**0.694**

Percentage variance accounted for 94.7

Standard error of observations is estimated to be 312.

Table A.6.36: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3746	165	22.76	**<.001**
N_Rate.Fertiliser OMF_{15}	10.177	0.85	11.97	**<.001**

A.6.4.9 Regression analysis – Response of rye grass to the application of urea – Clay loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.37: Summary of analysis

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	21125920	10562960	76.97	**<.001**
Residual	6	823418	137236		
Total	8	21949339	2743667		

Percentage variance accounted for 95.0

Standard error of observations is estimated to be 370.

Table A.6.38: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(6)**	**t pr.**
Constant	3713	214	17.36	**<.001**
N_Rate.Fertiliser Urea	30.09	3.64	8.28	**<.001**
N_Rate_Sq.Fertiliser Urea	-0.0627	0.0116	-5.39	**0.002**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.39: Summary of analysis

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	17142008	17142008	24.96	**0.002**
Residual	7	4807330	686761		
Total	8	21949339	2743667		
Change	1	3983912	3983912	29.03	**0.002**

Percentage variance accounted for 75.0

Standard error of observations is estimated to be 829

Table A.6.40: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(7)**	**t pr.**
Constant	4184	437	9.58	**<.001**
N_Rate.Fertiliser Urea	11.27	2.26	5	**0.002**

A.6.4.10 Regression analysis – Response of rye grass to the application of biosolids – Clay loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.41: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	11245842	5622921	14.23	**0.005**
Residual	6	2370851	395142		
Total	8	13616693	1702087		

Percentage variance accounted for 76.8

Standard error of observations is estimated to be 629

Table A.6.42: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3194	363	8.8	**<.001**
N_Rate.Fertiliser Biosolids	12.12	6.17	1.97	**0.097**
N_Rate_Sq.Fertiliser Biosolids	-0.0101	0.0198	-0.51	**0.626**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.43: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	11141980	11141980	31.52	**<.001**
Residual	7	2474713	353530		
Total	8	13616693	1702087		
Change	1	103862	103862	0.26	**0.626**

Percentage variance accounted for 79.2

Standard error of observations is estimated to be 595.

Table A.6.44: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3270	313	10.43	**<.001**
N_Rate.Fertiliser Biosolids	9.08	1.62	5.61	**<.001**

A.6.4.11 Regression analysis – Response of rye grass to the application of OMF_{10} – Clay loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.45: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	8825552	4412776	116.15	**<.001**
Residual	6	227943	37991		
Total	8	9053495	1131687		

Percentage variance accounted for 96.6

Standard error of observations is estimated to be 195.

Table A.6.46: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	113	33	**<.001**
N_Rate.Fertiliser OMF_{10}	4.8	1.91	2.51	**0.046**
N_Rate_Sq.Fertiliser OMF_{10}	0.01076	0.00613	1.76	**0.129**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.47: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	8708294	8708294	176.59	**<.001**
Residual	7	345200	49314		
Total	8	9053495	1131687		
Change	1	117257	117257	3.09	**0.129**

Percentage variance accounted for 95.6

Standard error of observations is estimated to be 222.

Table A.6.48: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3632	117	31.04	**<.001**
N_Rate.Fertiliser OMF_{10}	8.032	0.604	13.29	**<.001**

A.6.4.12 Regression analysis – Response of rye grass to the application of OMF_{15} – Clay loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.49: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	8191150	4095575	18.91	**0.003**
Residual	6	1299640	216607		
Total	8	9490790	1186349		

Percentage variance accounted for 81.7

Standard error of observations is estimated to be 465

Table A.6.50: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	269	13.82	**<.001**
N_Rate.Fertiliser OMF_{15}	10.08	4.57	2.21	**0.069**
N_Rate_Sq.Fertiliser OMF_{15}	-0.0077	0.0146	-0.53	**0.616**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.51: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	8130540	8130540	41.84	**<.001**
Residual	7	1360250	194321		
Total	8	9490790	1186349		
Change	1	60610	60610	0.28	**0.616**

Percentage variance accounted for 83.6

Standard error of observations is estimated to be 441

Table A.6.52: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3771	232	16.23	**<.001**
N_Rate.Fertiliser OMF_{15}	7.76	1.2	6.47	**<.001**

A.6.4.13 Regression analysis – Response of rye grass to the application of urea – Clay loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.53: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	5712283	2856142	28.4	**<.001**
Residual	6	603390	100565		
Total	8	6315673	789459		

Percentage variance accounted for 87.3

Standard error of observations is estimated to be 317.

Table A.6.54: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3713	183	20.28	**<.001**
N_Rate.Fertiliser Urea	9.42	3.11	3.03	**0.023**
N_Rate_Sq.Fertiliser Urea	-0.00992	0.00997	-1	**0.358**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.55: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	5612662	5612662	55.89	**<.001**
Residual	7	703012	100430		
Total	8	6315673	789459		
Change	1	99622	99622	0.99	**0.358**

Percentage variance accounted for 87.3

Standard error of observations is estimated to be 317.

Table A.6.56: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3788	167	22.68	**<.001**
N_Rate.Fertiliser Urea	6.448	0.863	7.48	**<.001**

A.6.4.14 Regression analysis – Response of rye grass to the application of biosolids – Sandy loam soil 2007

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.57: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	20180987	10090494	225.01	**<.001**
Residual	6	269066	44844		
Total	8	20450053	2556257		

Percentage variance accounted for 98.2

Standard error of observations is estimated to be 212.

Table A.6.58: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	2279	122	18.64	**<.001**
N_Rate.Fertiliser Biosolids	20.19	2.08	9.72	**<.001**
N_Rate_Sq.Fertiliser Biosolids	-0.02731	0.00666	-4.1	**0.006**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.59: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	19425603	19425603	132.73	**<.001**
Residual	7	1024450	146350		
Total	8	20450053	2556257		
Change	1	755384	755384	16.84	**0.006**

Percentage variance accounted for 94.3

Standard error of observations is estimated to be 383

Table A.6.60: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	2483	202	12.32	**<.001**
N_Rate.Fertiliser Biosolids	12	1.04	11.52	**<.001**

A.6.4.15 Regression analysis – Response of rye grass to the application of OMF_{10} – Sandy loam soil 2007

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.61: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	33751018	16875509	549.63	**<.001**
Residual	6	184219	30703		
Total	8	33935237	4241905		

Percentage variance accounted for 99.3

Standard error of observations is estimated to be 175

Table A.6.62: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	2279	101	22.52	**<.001**
N_Rate.Fertiliser OMF_{10}	18.46	1.72	10.74	**<.001**
N_Rate_Sq.Fertiliser OMF_{10}	-0.00889	0.00551	-1.61	**0.158**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.63: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	33671071	33671071	892.23	**<.001**
Residual	7	264166	37738		
Total	8	33935237	4241905		
Change	1	79947	79947	2.6	**0.158**

Percentage variance accounted for 99.1

Standard error of observations is estimated to be 194.

Table A.6.64: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	2345	102	22.91	**<.001**
N_Rate.Fertiliser OMF_{10}	15.793	0.529	29.87	**<.001**

A.6.4.16 Regression analysis – Response of rye grass to the application of OMF_{15} – Sandy loam soil 2007

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.65: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	52361694	26180847	1423.01	**<.001**
Residual	6	110390	18398		
Total	8	52472083	6559010		

Percentage variance accounted for 99.7

Standard error of observations is estimated to be 136

Table A.6.66: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	2278.5	78.3	29.1	**<.001**
N_Rate.Fertiliser OMF_{15}	18.56	1.33	13.94	**<.001**
N_Rate_Sq.Fertiliser OMF_{15}	0.00378	0.00426	0.89	**0.41**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.67: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	52347244	52347244	2935.21	**<.001**
Residual	7	124840	17834		
Total	8	52472083	6559010		
Change	1	14450	14450	0.79	**0.41**

Percentage variance accounted for 99.7

Standard error of observations is estimated to be 134

Table A.6.68: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	2250.2	70.4	31.97	**<.001**
N_Rate.Fertiliser OMF_{15}	19.692	0.363	54.18	**<.001**

A.6.4.17 Regression analysis – Response of rye grass to the application of urea – Sandy loam soil 2007

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.69: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	90625217	45312608	1156.84	**<.001**
Residual	6	235016	39169		
Total	8	90860232	11357529		

Percentage variance accounted for 99.7

Standard error of observations is estimated to be 198

Table A.6.70: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	2279	114	19.94	**<.001**
N_Rate.Fertiliser Urea	25.56	1.94	13.16	**<.001**
N_Rate_Sq	0.00116	0.00622	0.19	**0.858**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.71: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	90623852	90623852	2683.68	**<.001**
Residual	7	236380	33769		
Total	8	90860232	11357529		
Change	1	1364	1364	0.03	**0.858**

Percentage variance accounted for 99.7

Standard error of observations is estimated to be 184

Table A.6.72: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	2269.8	96.9	23.44	**<.001**
N_Rate.Fertiliser Urea	25.909	0.5	51.8	**<.001**

A.6.4.18 Regression analysis – Response of rye grass to the application of biosolids – Sandy loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.73: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	18766507	9383253	32.87	**<.001**
Residual	6	1712709	285452		
Total	8	20479216	2559902		

Percentage variance accounted for 88.8

Standard error of observations is estimated to be 534.

Table A.6.74: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3526	308	11.43	**<.001**
N_Rate.Fertiliser Biosolids	7.56	5.24	1.44	**0.2**
N_Rate_Sq.Fertiliser Biosolids	0.0139	0.0168	0.83	**0.439**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.75: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	18570819	18570819	68.12	**<.001**
Residual	7	1908397	272628		
Total	8	20479216	2559902		
Change	1	195688	195688	0.69	**0.439**

Percentage variance accounted for 89.4

Standard error of observations is estimated to be 522.

Table A.6.76: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3422	275	12.44	**<.001**
N_Rate.Fertiliser Biosolids	11.73	1.42	8.25	**<.001**

A.6.4.19 Regression analysis – Response of rye grass to the application of OMF$_{10}$ – Sandy loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.77: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	14430568	7215284	42.8	**<.001**
Residual	6	1011379	168563		
Total	8	15441947	1930243		

Percentage variance accounted for 91.3

Standard error of observations is estimated to be 411.

Table A.6.78: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3526	237	14.88	**<.001**
N_Rate.Fertiliser OMF$_{10}$	22.38	4.03	5.55	**0.001**
N_Rate_Sq.Fertiliser OMF$_{10}$	-0.0424	0.0129	-3.28	**0.017**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.79: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	12613260	12613260	31.21	**<.001**
Residual	7	2828687	404098		
Total	8	15441947	1930243		
Change	1	1817308	1817308	10.78	**0.017**

Percentage variance accounted for 79.1

Standard error of observations is estimated to be 636.

Table A.6.80: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3844	335	11.47	<.001
N_Rate.Fertiliser OMF$_{10}$	9.67	1.73	5.59	<.001

A.6.4.19 Regression analysis – Response of rye grass to the application of OMF_{15} – Sandy loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.81: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	15473455	7736728	46.64	**<.001**
Residual	6	995318	165886		
Total	8	16468774	2058597		

Percentage variance accounted for 91.9

Standard error of observations is estimated to be 407.

Table A.6.82: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3526	235	15	**<.001**
N_Rate.Fertiliser OMF_{15}	16.23	4	4.06	**0.007**
N_Rate_Sq.Fertiliser OMF_{15}	-0.0188	0.0128	-1.47	**0.192**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.83: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	15114271	15114271	78.11	**<.001**
Residual	7	1354503	193500		
Total	8	16468774	2058597		
Change	1	359185	359185	2.17	**0.192**

Percentage variance accounted for 90.6

Standard error of observations is estimated to be 440.

Table A.6.84: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3668	232	15.82	**<.001**
N_Rate.Fertiliser OMF_{15}	10.58	1.2	8.84	**<.001**

A.6.4.19 Regression analysis – Response of rye grass to the application of urea – Sandy loam soil 2008

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.85: Summary of analysis

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	15517483	7758742	16.25	**0.004**
Residual	6	2864559	477427		
Total	8	18382043	2297755		

Percentage variance accounted for 79.2

Standard error of observations is estimated to be 691.

Table A.6.86: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(6)**	**t pr.**
Constant	3526	399	8.84	**<.001**
N_Rate.Fertiliser Urea	19.69	6.78	2.9	**0.027**
N_Rate_Sq.Fertiliser Urea	-0.031	0.0217	-1.43	**0.203**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.87: Summary of analysis

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	14541446	14541446	26.5	**0.001**
Residual	7	3840597	548657		
Total	8	18382043	2297755		
Change	1	976037	976037	2.04	**0.203**

Percentage variance accounted for 76.1

Standard error of observations is estimated to be 741.

Table A.6.88: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(7)**	**t pr.**
Constant	3759	390	9.63	**<.001**
N_Rate.Fertiliser Urea	10.38	2.02	5.15	**0.001**

A.6.4.20 Regression analysis – Response of rye grass to the application of biosolids – Sandy loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.89: Summary of analysis

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	7467182	3733591	25.68	**0.001**
Residual	6	872360	145393		
Total	8	8339542	1042443		

Percentage variance accounted for 86.1

Standard error of observations is estimated to be 381.

Table A.6.90: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(6)**	**t pr.**
Constant	3265	220	14.83	**<.001**
N_Rate.Fertiliser Biosolids	9.33	3.74	2.49	**0.047**
N_Rate_Sq.Fertiliser Biosolids	-0.0064	0.012	-0.53	**0.614**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.91: Summary of analysis

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	7426160	7426160	56.91	**<.001**
Residual	7	913382	130483		
Total	8	8339542	1042443		
Change	1	41022	41022	0.28	**0.614**

Percentage variance accounted for 87.5

Standard error of observations is estimated to be 361.

Table A.6.92: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(7)**	**t pr.**
Constant	3312	190	17.4	**<.001**
N_Rate.Fertiliser Biosolids	7.417	0.983	7.54	**<.001**

A.6.4.21 Regression analysis – Response of rye grass to the application of OMF_{10} – Sandy loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.93: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	10525235	5262617	68.15	**<.001**
Residual	6	463344	77224		
Total	8	10988578	1373572		

Percentage variance accounted for 94.4

Standard error of observations is estimated to be 278.

Table A.6.94: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(6)**	**t pr.**
Constant	3265	160	20.35	**<.001**
N_Rate.Fertiliser OMF10	5.64	2.73	2.07	**0.084**
N_Rate_Sq.Fertiliser OMF10	0.01048	0.00873	1.2	**0.275**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.95: Summary of analysis

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	10414047	10414047	126.88	**<.001**
Residual	7	574531	82076		
Total	8	10988578	1373572		
Change	1	111188	111188	1.44	**0.275**

Percentage variance accounted for 94.0

Standard error of observations is estimated to be 286.

Table A.6.96: Estimates of parameters

Parameter	**estimate**	**s.e.**	**t(7)**	**t pr.**
Constant	3186	151	21.1	<.001
N_Rate.Fertiliser OMF10	8.783	0.78	11.26	<.001

A.6.4.22 Regression analysis – Response of rye grass to the application of OMF$_{15}$ – Sandy loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.97: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	12766951	6383476	47.32	**<.001**
Residual	6	809407	134901		
Total	8	13576358	1697045		

Percentage variance accounted for 92.1

Standard error of observations is estimated to be 367.

Table A.6.98: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3265	212	15.4	**<.001**
N_Rate.Fertiliser OMF15	8.88	3.6	2.46	**0.049**
N_Rate_Sq.Fertiliser OMF15	0.0028	0.0115	0.24	**0.816**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.99: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	12758958	12758958	109.26	**<.001**
Residual	7	817399	116771		
Total	8	13576358	1697045		
Change	1	7993	7993	0.06	**0.816**

Percentage variance accounted for 93.1

Standard error of observations is estimated to be 342.

Table A.6.100: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3244	180	18.01	**<.001**
N_Rate.Fertiliser OMF15	9.722	0.93	10.45	**<.001**

A.6.4.22 Regression analysis – Response of rye grass to the application of urea – Sandy loam soil 2009

Regression analysis – quadratic model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser + N_Rate_Sq.Fertiliser

Table A.6.101: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	10889369	5444684	32.31	**<.001**
Residual	6	1011219	168536		
Total	8	11900588	1487573		

Percentage variance accounted for 88.7

Standard error of observations is estimated to be 411.

Table A.6.102: Estimates of parameters

Parameter	estimate	s.e.	t(6)	t pr.
Constant	3265	237	13.77	**<.001**
N_Rate.Fertiliser Urea	12.99	4.03	3.22	**0.018**
N_Rate_Sq.Fertiliser Urea	-0.0136	0.0129	-1.06	**0.332**

Regression analysis – linear model

Response variate: Annual_Yield

Fitted terms: Constant + N_Rate.Fertiliser

Table A.6.103: Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	10701362	10701362	62.46	**<.001**
Residual	7	1199226	171318		
Total	8	11900588	1487573		
Change	1	188007	188007	1.12	**0.332**

Percentage variance accounted for 88.5

Standard error of observations is estimated to be 414.

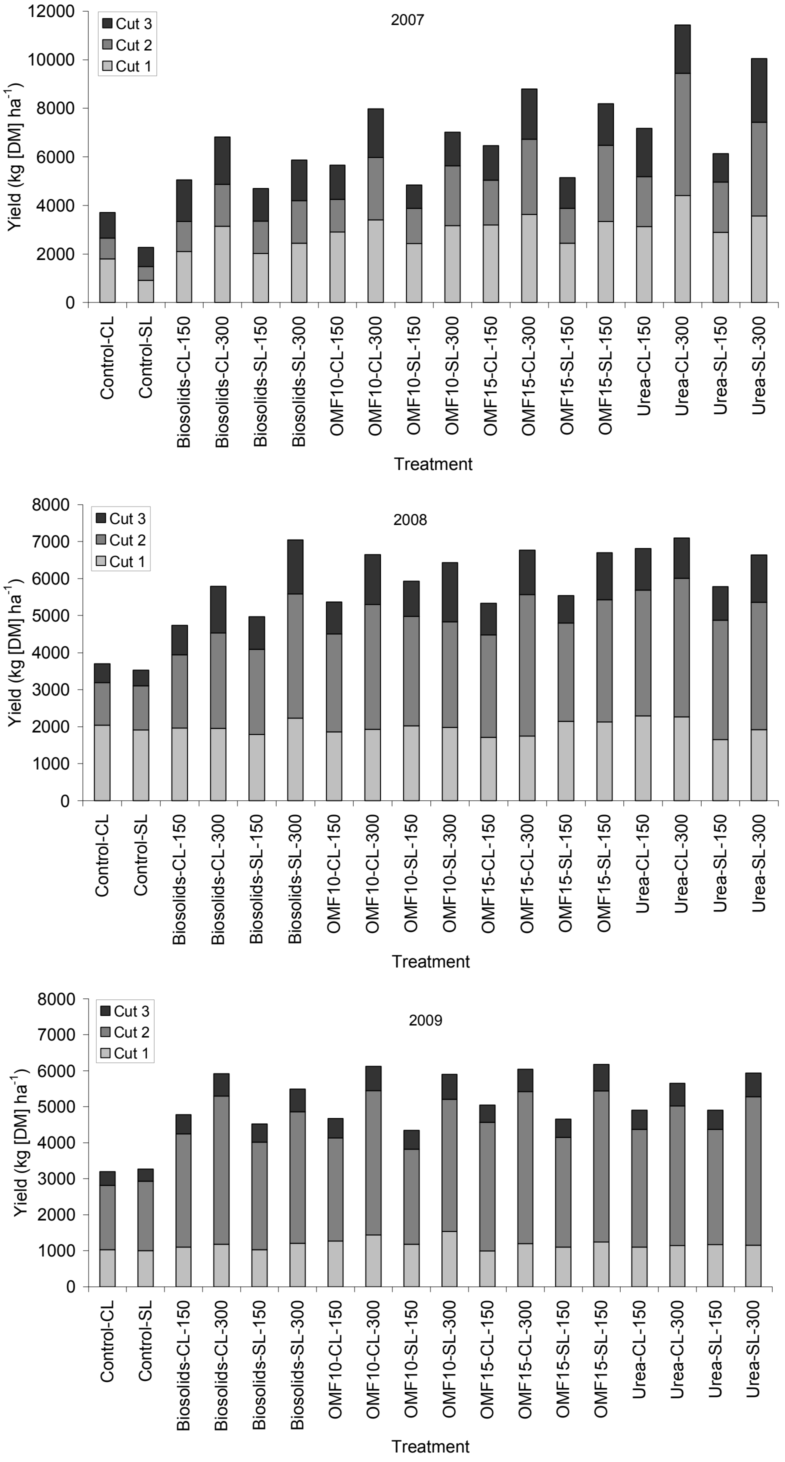
Table A.6.104: Estimates of parameters

Parameter	estimate	s.e.	t(7)	t pr.
Constant	3367	218	15.43	**<.001**
N_Rate.Fertiliser Urea	8.9	1.13	7.9	**<.001**

Appendix A.6.5: Photographic record – glasshouse studies

Figure A.6.3: Photographic record of pots-grown rye grass in the glasshouse. Picture taken prior to the first cut in 2007: (*a*) Sandy loam 150 kg [N] ha^{-1}, (*b*) Sandy loam 300 kg [N] ha^{-1}, (*c*) Clay loam 150 kg [N] ha^{-1}, (*d*) Clay loam 300 kg [N] ha^{-1} and controls (zero-fertiliser).

Appendix A.6.6: Dry matter yield of rye grass – Analysis of data corresponding to individual cuts between 2007 and 2009 in glasshouse studies



$\text{LSD}_{[5\% \text{ level}]}$ =505.8
p-value =0.017

$\text{LSD}_{[5\% \text{ level}]}$ =505.8
p-value =0.017

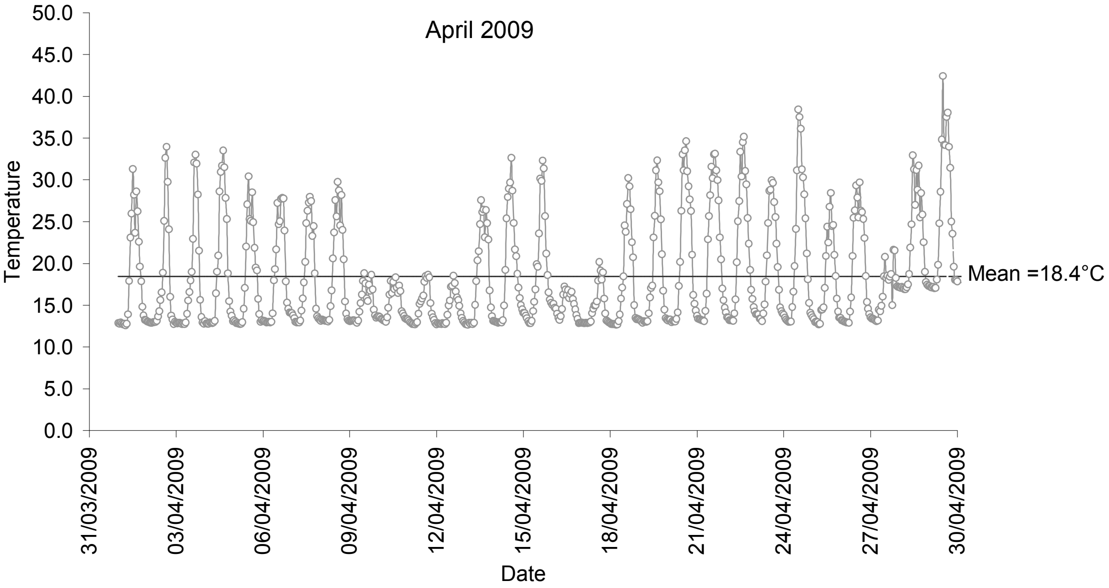
$\text{LSD}_{[5\% \text{ level}]}$ =505.8
p-value =0.017

Figure A.6.4: Dry matter yield of rye grass in the glasshouse studies (2007-2009) [CL: clay loam soil, SL: sandy loam soil. The nitrogen application rate is indicated as 150 and 300 kg [N] ha^{-1}].

Table A.6.105: Timing of cuts and fertiliser applications in the glasshouse studies 2007-2009.

Year	Cut No.:	Date of cut	Date of fertiliser application
2007 (Establishment)	1	14.06.2007	27.04.2007 (at sowing)
	2	23.07.2007	
	3	03.10.2007	
2008	1	31.05.2008	02.06.2008
	2	07.08.2008	
	3	09.10.2008	
2009	1	29.05.2009	30.05.2009
	2	30.07.2009	
	3	12.10.2009	**End experiment**

Appendix A.6.7: Daily temperature records inside the glasshouse



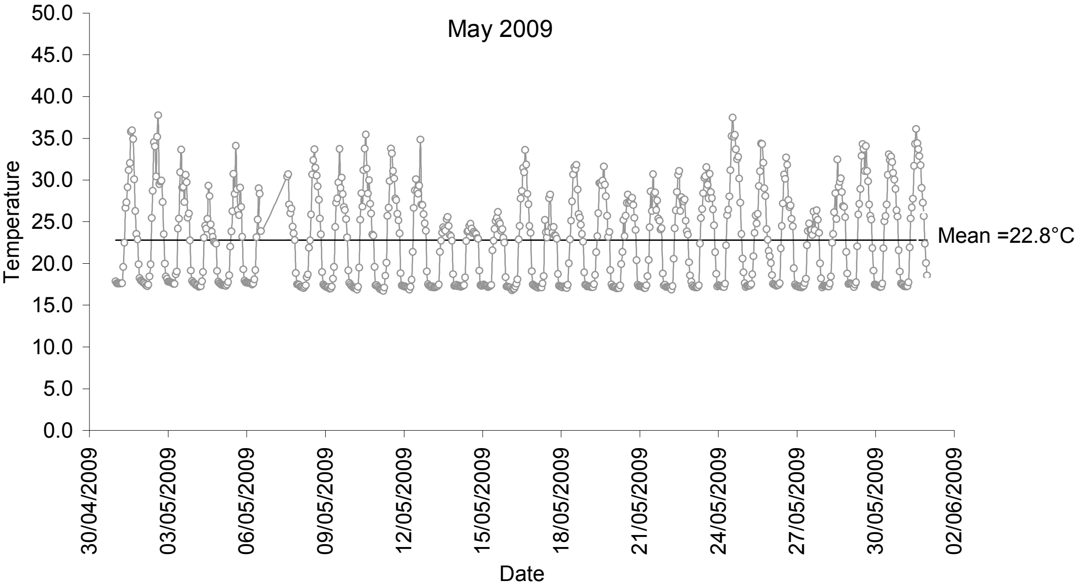
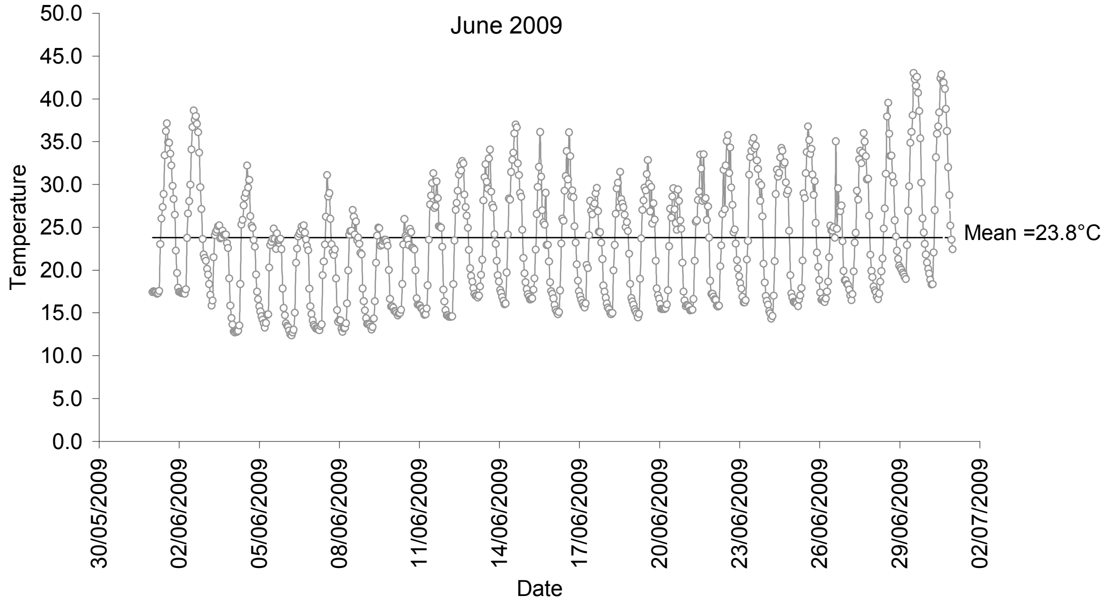


Figure A.6.5: Temperature records in the glasshouse in April and May 2009 (after: Ghalamboran, 2011).



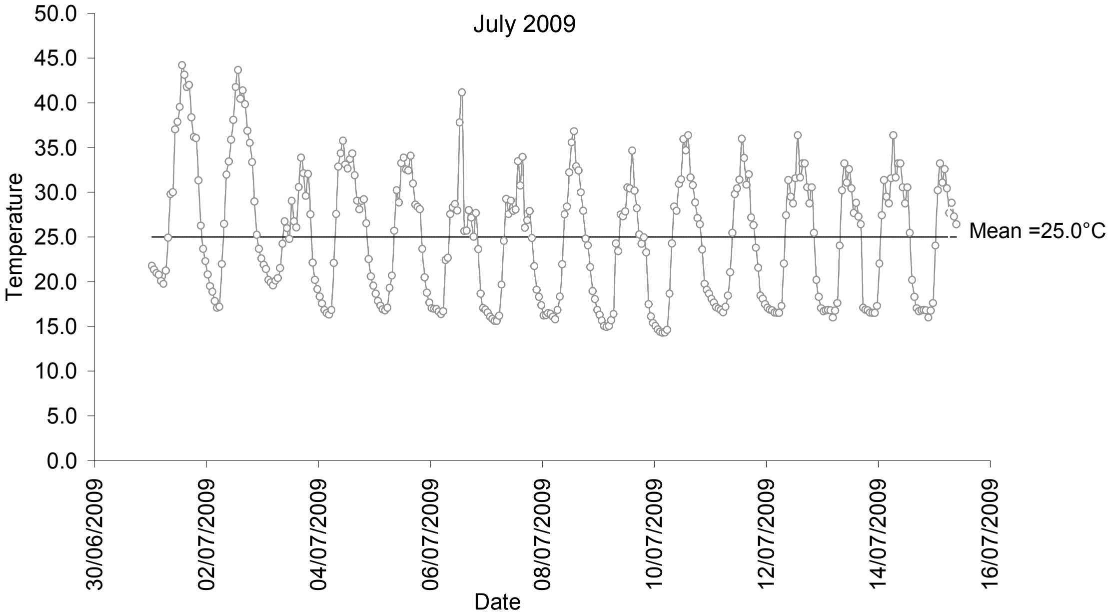


Figure A.6.6: Temperature records in the glasshouse in June and July 2009 (after: Ghalamboran, 2011).

Appendix A.6.8: Statistical analyses corresponding to total P uptake – 1^{st} cut conducted in 2007

Table A.6.105: Analysis of variance – total P uptake by rye grass in the first cut conducted in 2007.

Variate: P-uptake (kg [P] ha^{-1})

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Soils	1	0.3970	0.3970	11.65	**0.002**
Control_v_Treated	1	2.9288	2.9288	85.97	**<.001**
Soils.Control_v_Treated	1	0.5327	0.5327	15.64	**<.001**
Control_v_Treated.Fertiliser	3	0.6869	0.2290	6.72	**0.001**
Control_v_Treated.Rate	1	0.4200	0.4200	12.33	**0.001**
Soils.Control_v_Treated.Fertiliser	3	0.0381	0.0127	0.37	**0.773**
Soils.Control_v_Treated.Rate	1	0.0111	0.0111	0.33	**0.572**
Control_v_Treated.Fertiliser.Rate	3	0.1422	0.0474	1.39	**0.261**
Soils.Control_v_Treated.Fertiliser.Rate	3	0.2378	0.0793	2.33	**0.091**
Residual	**36**	**1.2264**	**0.0341**		
Total	**53**	**6.6209**			

The results of the analysis of TP_{plant} for the first cut in 2007 are summarised in **Figure A.6.7:**

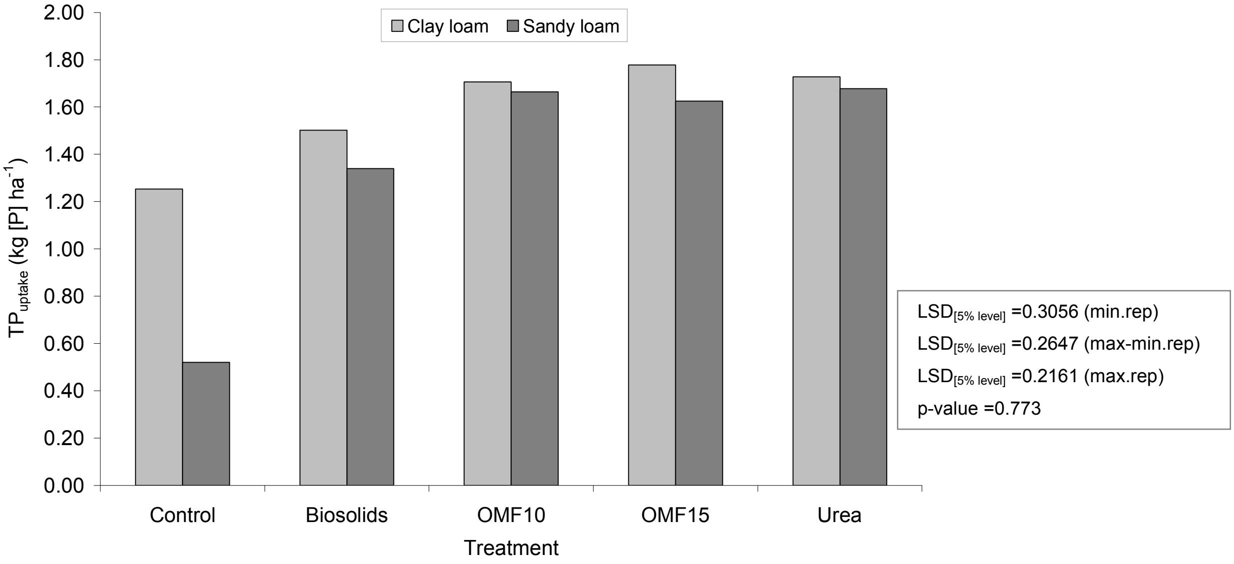


Figure A.6.7: TP_{uptake} for pot-grown rye grass corresponding to the first cut conducted in 2007 (n=6 except control n=3).

Appendix A.6.9: Statistical analyses corresponding to total P in harvested plant material – 1st cut conducted in 2007

Table A.6.106: Analysis of variance – total P in harvested plant material (rye grass) in the first cut conducted in 2007.

Variate: TP_{plant} (mg [P] kg^{-1} [DM])

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Soils	1	9462	9462	3.08	**0.088**
Control_v_Treated	1	36502	36502	11.89	**0.001**
Soils.Control_v_Treated	1	38243	38243	12.46	**0.001**
Control_v_Treated.Fertiliser	3	67374	22458	7.32	**<.0.01**
Control_v_Treated.Rate	1	63075	63075	20.55	**<.0.01**
Soils.Control_v_Treated.Fertiliser	3	1770	590	0.19	**0.901**
Soils.Control_v_Treated.Rate	1	1261	1261	0.41	**0.596**
Control_v_Treated.Fertiliser.Rate	3	5220	1740	0.57	**0.640**
Soils.Control_v_Treated.Fertiliser.Rate	3	3790	1263	0.41	**0.746**
Residual	**36**	**110495**	**3069**		
Total	**53**	**337191**			

The results of the analysis of TP_{plant} for the first cut in 2007 are summarised in **Figure A.6.8:**

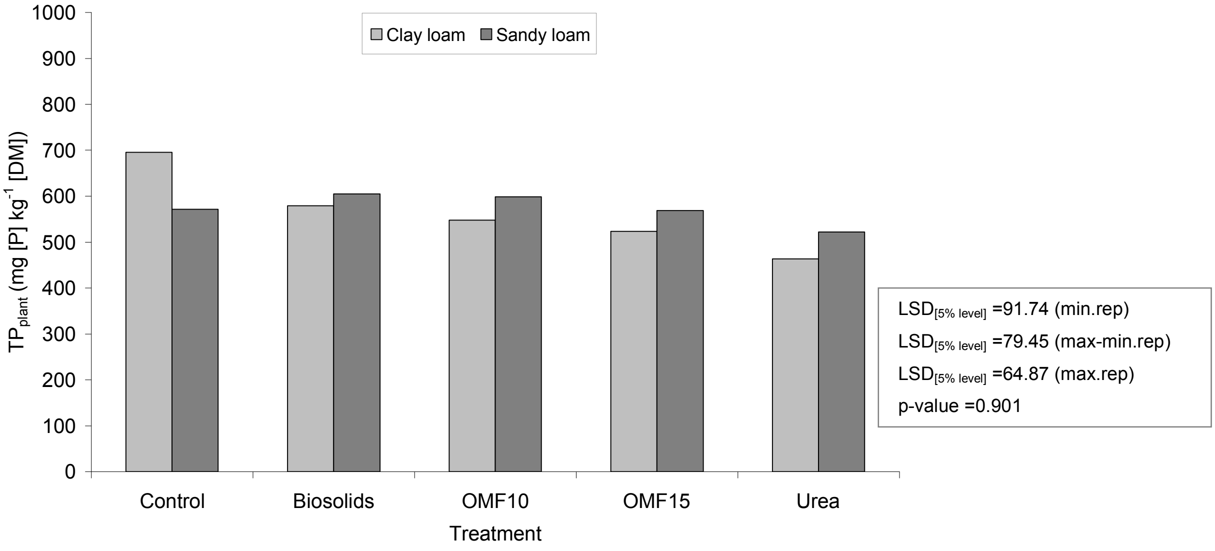


Figure A.6.8: TP_{plant} for pot-grown rye grass corresponding to the first cut conducted in 2007 (n=6 except control n=3).

APPENDIX CHAPTER 7

Appendix A.7.1: Meteorological data for Bedfordshire 2006-2010

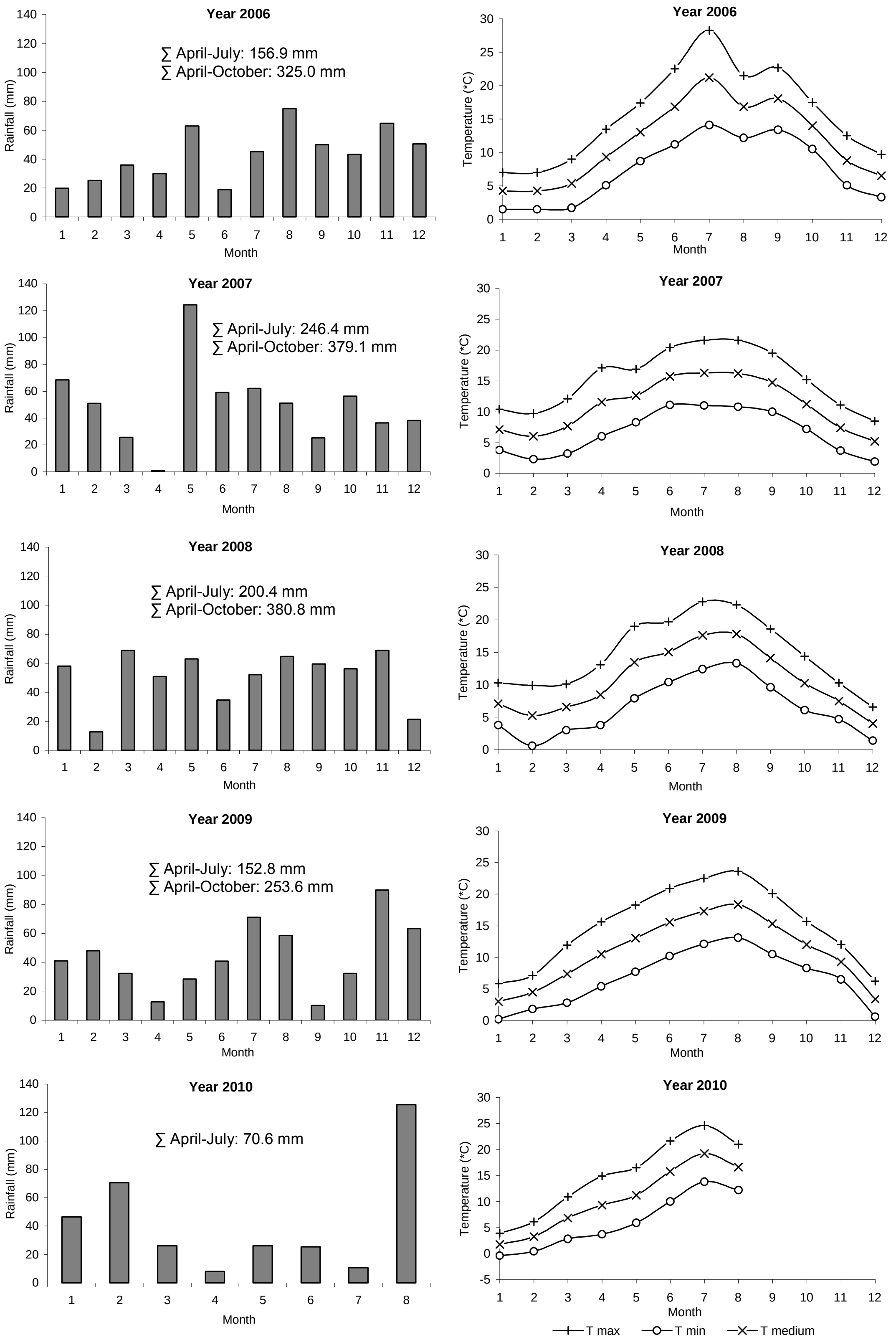


Figure A.7.1: Rainfall and temperature recorded for Bedfordshire for the period 2006-2010 (Source: Met. Office, 2010).

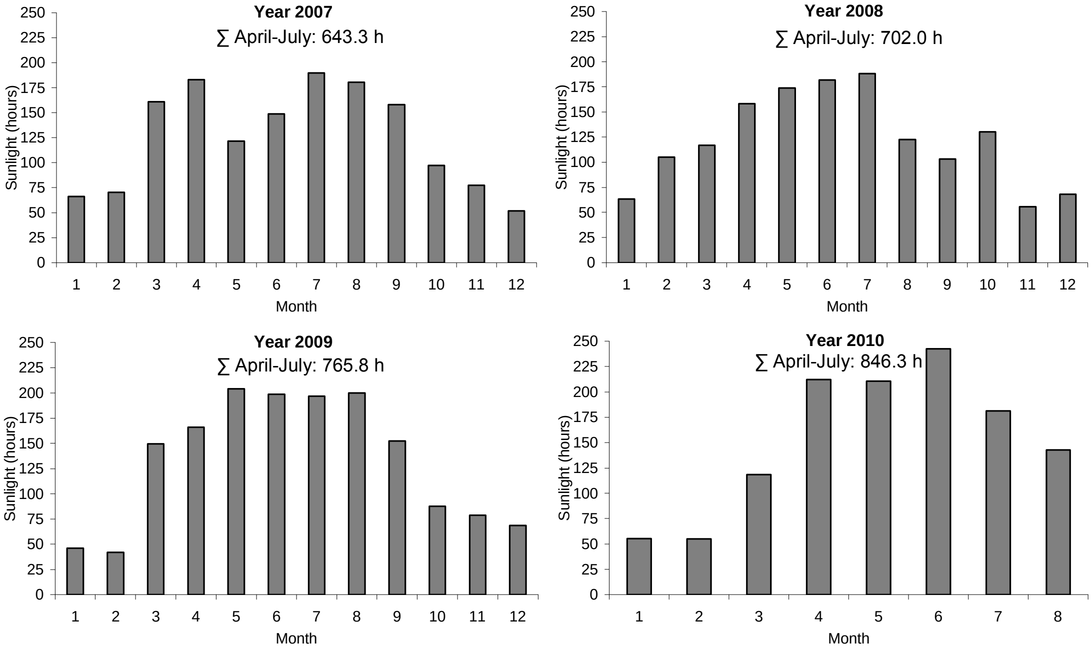


Figure A.7.2: Sunlight (hours) recorded for Bedfordshire for the period 2007-2010 (Source: Met. Office, 2010).

Appendix A.7.2: Layout of experimental plots at the College Farm

i. Avenue Field (wheat 2006-07 & 2007-08 and rye-grass 2009-10)

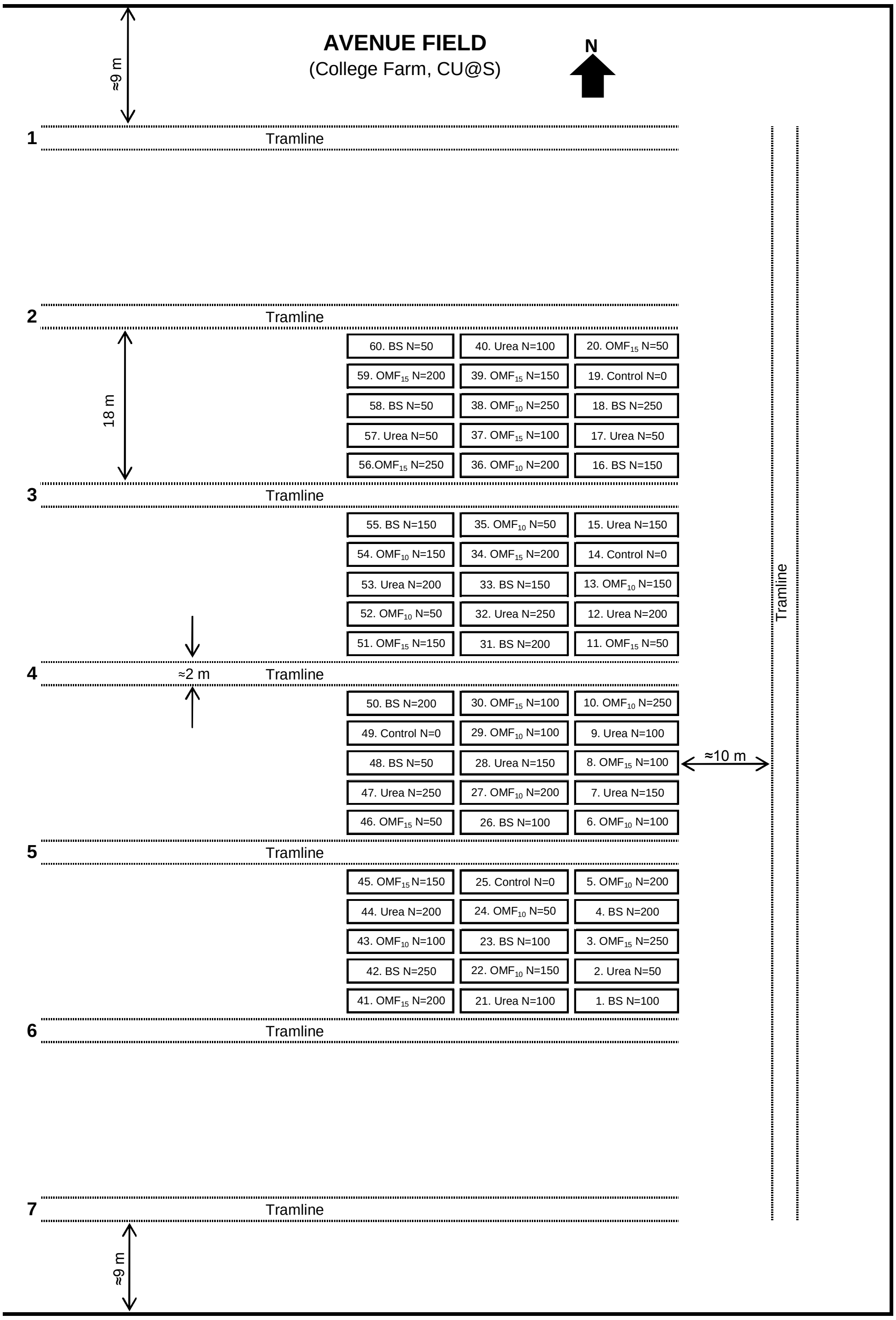
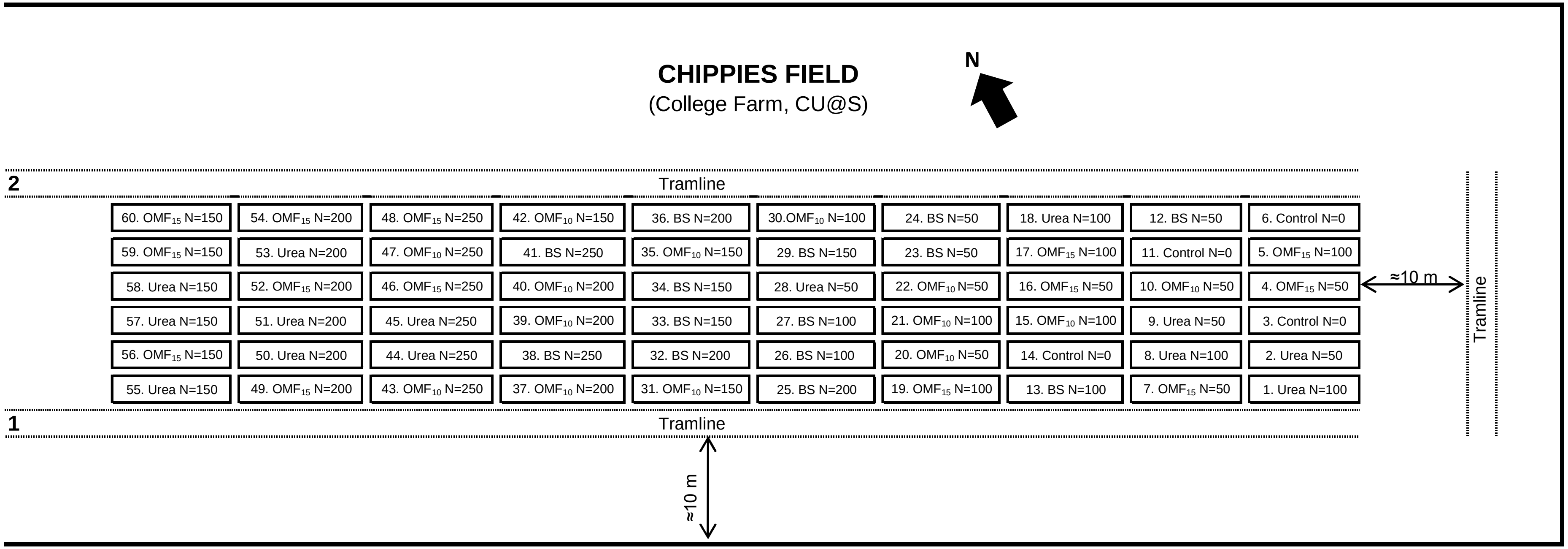


Figure A.7.3: Layout of the experiment and details of the treatments in Avenue Field (not to scale). The plot number is followed by the fertiliser type and the equivalent nitrogen rate applied on the plot expressed in kg [N] ha^{-1} (BS = biosolids-treated plot). Note: plots' dimensions ≈ 2 m × 5 m.

ii. Chippies Field (wheat 2008-09 & 2009-10)

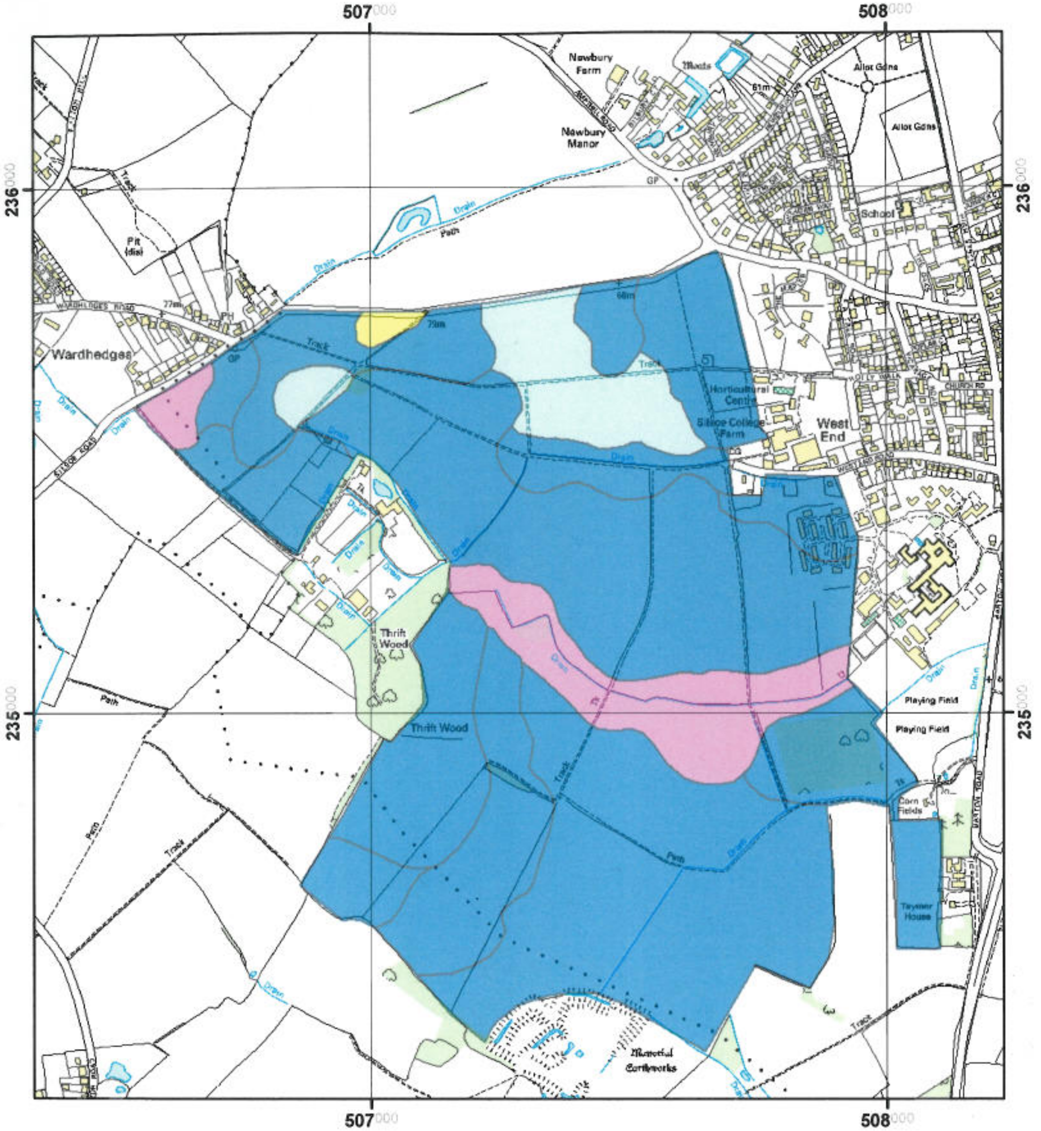


60. OMF$_{15}$ N=150	54. OMF$_{15}$ N=200	48. OMF$_{15}$ N=250	42. OMF$_{10}$ N=150	36. BS N=200	30.OMF$_{10}$ N=100	24. BS N=50	18. Urea N=100	12. BS N=50	6. Control N=0
59. OMF$_{15}$ N=150	53. Urea N=200	47. OMF$_{10}$ N=250	41. BS N=250	35. OMF$_{10}$ N=150	29. BS N=150	23. BS N=50	17. OMF$_{15}$ N=100	11. Control N=0	5. OMF$_{15}$ N=100
58. Urea N=150	52. OMF$_{15}$ N=200	46. OMF$_{15}$ N=250	40. OMF$_{10}$ N=200	34. BS N=150	28. Urea N=50	22. OMF$_{10}$ N=50	16. OMF$_{15}$ N=50	10. OMF$_{10}$ N=50	4. OMF$_{15}$ N=50
57. Urea N=150	51. Urea N=200	45. Urea N=250	39. OMF$_{10}$ N=200	33. BS N=150	27. BS N=100	21. OMF$_{10}$ N=100	15. OMF$_{10}$ N=100	9. Urea N=50	3. Control N=0
56. OMF$_{15}$ N=150	50. Urea N=200	44. Urea N=250	38. BS N=250	32. BS N=200	26. BS N=100	20. OMF$_{10}$ N=50	14. Control N=0	8. Urea N=100	2. Urea N=50
55. Urea N=150	49. OMF$_{15}$ N=200	43. OMF$_{10}$ N=250	37. OMF$_{10}$ N=200	31. OMF$_{10}$ N=150	25. BS N=200	19. OMF$_{15}$ N=100	13. BS N=100	7. OMF$_{15}$ N=50	1. Urea N=100

Figure A.7.4: Layout of the experiment and details of the treatments in Chippies Field (not to scale). The plot number is followed by the fertiliser type and the equivalent nitrogen rate applied on the plot expressed in kg [N] ha^{-1} (BS = biosolids-treated plot). Note: plots' dimensions ≈ 2 m × 3 m.

iii. Soil map of the College Farm – Cranfield University at Silsoe

The soil map of the College Farm, Cranfield University at Silsoe, MK45 4DT, UK is shown in **Figure A.7.5** (source: NSRI, 2006).



Soils of College Farm, Silsoe, Bedfordshire

A double map illustrating the soils of College Farm, Silsoe, Bedfordshire, showing the distribution of soil series and a translation into the World Reference Base (WRB) classification.

Map produced by Ian Truckell, National Soil Resources Institute, Cranfield University.

Soils data from LandIS - Land Information System.
For more details contact nsridata@cranfield.ac.uk or visit www.landis.org.uk

WRB Reference Group	WRB Group Description	Soil subgroup name	Series name	Series symbol	Description
Stagnosol	Soils with a perched water table showing redoximorphic features caused by surface water. Periodically wet and mottled in the topsoil and subsoil, with or without concretions or bleaching. The common name in many systems is *pseudogley*.	Pelostagnogleysol	Denchworth	Da	Clayey passing to clay or soft mudstone
		Pelostagnogleysol	Lawford	LD	Swelling clay drift passing to clay or soft mudstone
Cambisol	Young soil in which pedogenic processes are evident from variations in colour and/or development of structure below surface horizons. Commonly known as Brown Soils, Braunerde (Germany), Sols Brun (France) or Brnizems (Russia), from the Latin *cambiare* meaning to change.	Typical calcareous pelosol	Evesham	Ea	Clayey passing to clay or soft mudstone
		Typical calcareous pelosol	Drayton	dT	Swelling clay drift passing to clay or soft mudstone
		Typical calcareous pelosol	Hanslope	Hn	Clayey chalky drift
		Typical argillic pelosol	Holdenby	HM	Clayey drift passing to clay or soft mudstone
		Typical argillic pelosol	Faulkbourne	fK	Clayey chalky drift
		Typical Brown Earth	Bearsted	BE	Coarse loamy passing to sandstone
		Typical Brown Earth	Rivington	Rc	Coarse loamy over lithoskeletal sandstone
Luvisol	Soil with a subsurface horizon of high activity clay accumulation and high base saturation, from the Latin, *luere*, meaning to wash.	Typical Argillic Brown Earth	Maplestead	MM	Coarse loamy drift with siliceous stones
		Typical Argillic Brown Earth	Ludford	LF	Fine loamy drift with siliceous stones
Arenosol	Easily erodable sandy soil with slow weathering rate, low water and nutrient holding capacity and low base saturation, from the Latin, *arena*, meaning sand.	Typical Brown Sand	Cottenham	CN	Sandy ferruginous

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Appendix A.7.3: Records of fertiliser applications – Field studies

Table A.7.1: Fertiliser applied on the field experiments in g [product] per plot. (*)Excluding the first nitrogen dressing equivalent to 100 kg [N] ha^{-1} using UAN (30% N). (**)The application of biosolids in 2006-07 in Avenue Field was conducted assuming a nitrogen concentration in the material equivalent to 2.90% (w w^{-1}) and not 3.89% (w w^{-1}) which resulted in larger amounts of product being applied and hence in excess of nitrogen compared with the rest of the treatments. The resultant nitrogen rates for biosolids-treated plots excluding the first nitrogen dressing were: 0 (control), 67, 134, 201, 268, and 335 kg [N] ha^{-1}.

	Avenue Field [Plot size =10 m^{2}]							
Crop	**(*)Winter wheat 2006-07**				**Winter wheat 2007-08**			
Application rate (kg [N] ha^{-1})	**(**)Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**	**Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**
0	-	-	-	-	-	-	-	-
50	1724.14	615.00	508.64	108.70	1103.75	475.28	311.52	108.70
100	3448.28	1230.01	1017.29	217.39	2207.50	950.57	623.05	217.39
150	5172.41	1845.01	1525.94	326.08	3311.25	1425.85	934.58	326.08
200	6896.55	2460.02	2034.58	434.78	4415.01	1901.14	1246.10	434.78
250	8620.69	3075.03	2543.23	543.47	5518.76	2376.42	1557.63	543.47
Crop	**Rye grass 2009**				**Rye grass 2010**			
Application rate (kg [N] ha^{-1})	**Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**	**Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**
0	-	-	-	-	-	-	-	-
50	1259.44	507.61	358.16	108.70	912.40	699.30	438.98	108.70
100	2518.89	1015.22	716.33	217.39	1824.81	1398.60	877.96	217.39
150	3778.33	1522.84	1074.49	326.08	2737.22	2097.90	1316.94	326.08
200	5037.78	2030.45	1432.66	434.78	3649.63	2797.20	1755.92	434.78
250	6297.22	2538.07	1790.83	543.47	4562.04	3496.50	2194.90	543.47
	Chippies Field [Plot size =6 m^{2}]							
Crop	**Winter wheat 2008-09**				**Winter wheat 2009-10**			
Application rate (kg [N] ha^{-1})	**Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**	**Biosolids**	**OMF$_{10}$**	**OMF$_{15}$**	**Urea**
0	-	-	-	-	-	-	-	-
50	755.66	304.57	214.90	65.22	547.44	419.58	263.39	65.22
100	1511.33	609.13	429.80	130.43	1094.89	839.16	526.78	130.43
150	2267.00	913.70	644.69	195.65	1642.33	1258.74	790.16	195.65
200	3022.67	1218.27	859.60	260.87	2189.78	1678.32	1053.55	260.87
250	3778.33	1522.84	1074.50	326.08	2737.22	2097.90	1316.94	326.08

Table A.7.2: P_2O_5 and K_2O applied to the plots in Avenue Field in relation to the nitrogen application rates used in the experiments and based on the amounts of fertiliser shown in Table A.6.1. The values of P_2O_5 and K_2O are expressed in g [P_2O_5] or [K_2O] per plot which are equivalent to kg [P_2O_5] or [K_2O] ha^{-1}.

Crop	Avenue Field – Winter wheat 2006-07 [Plot size =10 m^2]					
Application rate (kg [N] ha^{-1})	Biosolids		OMF_{10}		OMF_{15}	
	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]
0	-	-	-	-	-	-
50	89.66	2.41	25.22	14..33	18.87	10.43
100	179.31	4.83	50.43	28.66	37.74	20.85
150	268.97	7.24	75.65	42.99	56.61	31.28
200	358.62	9.66	100.86	57.32	75.48	41.71
250	448.28	12.07	126.08	71.65	94.35	52.14

Crop	Avenue Field – Winter wheat 2007-08 [Plot size =10 m^2]					
Application rate (kg [N] ha^{-1})	Biosolids		OMF_{10}		OMF_{15}	
	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]
0	-	-	-	-	-	-
50	65.78	2.87	18.73	16.97	11.28	11.99
100	131.57	5.74	37.45	33.94	22.55	23.99
150	197.35	8.61	56.18	50.90	33.83	35.98
200	263.13	11.48	74.98	67.87	45.11	47.97
250	328.92	14.35	93.63	84.84	56.39	59.97

Crop	Avenue Field – Rye grass 2009 [Plot size =10 m^2]					
Application rate (kg [N] ha^{-1})	Biosolids		OMF_{10}		OMF_{15}	
	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]
0	-	-	-	-	-	-
50	82.75	1.26	25.84	16.24	14.58	14.36
100	165.49	2.52	51.67	32.49	29.15	28.72
150	248.24	3.78	77.51	48.73	43.73	43.09
200	330.98	5.04	103.35	64.97	58.31	57.45
250	413.73	6.30	129.19	81.22	72.89	71.81

Crop	Avenue Field – Rye grass 2010 [Plot size =10 m^2]					
Application rate (kg [N] ha^{-1})	Biosolids		OMF_{10}		OMF_{15}	
	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]	[P_2O_5]	[K_2O]
0	-	-	-	-	-	-
50	39.42	1.82	29.16	16.71	15.58	12.42
100	78.83	3.65	58.32	33.43	31.17	24.85
150	118.25	5.47	87.48	50.14	46.75	37.27
200	157.66	7.30	116.64	66.85	62.34	49.69
250	197.08	9.12	145.80	83.57	77.92	62.12

Table A.7.3: P_2O_5 and K_2O applied to the plots in Chippies Field in relation to the nitrogen application rates used in the experiments and based on the amounts of fertiliser shown in Table A.6.1. The values of P_2O_5 and K_2O are expressed in g $[P_2O_5]$ or $[K_2O]$ per plot which are equivalent to the values shown in brackets given in kg $[P_2O_5]$ or $[K_2O]$ ha^{-1}.

Crop	**Chippies Field – Winter wheat 2008-09 [Plot size =6 m^2]**					
Application rate (kg [N] ha^{-1})	**Biosolids**		**OMF_{10}**		**OMF_{15}**	
	$[P_2O_5]$	**$[K_2O]$**	**$[P_2O_5]$**	**$[K_2O]$**	**$[P_2O_5]$**	**$[K_2O]$**
0	-	-	-	-	-	-
50	49.65 (*82.75*)	0.76 (*1.27*)	15.50 (*25.83*)	9.75 (*16.25*)	8.75 (*14.58*)	8.62 (*14.37*)
100	99.29 (*165.48*)	1.51 (*2.52*)	31.00 (*51.67*)	19.49 (*32.48*)	17.49 (*29.15*)	17.23 (*28.72*)
150	148.94 (*248.23*)	2.27 (*3.78*)	46.51 (*77.52*)	29.24 (*48.73*)	26.24 (*43.73*)	25.85 (*43.08*)
200	198.59 (*330.98*)	3.02 (*5.03*)	62.01 (*103.35*)	38.98 (*64.97*)	34.99 (*58.32*)	34.47 (*57.45*)
250	248.24 (*417.73*)	3.78 (*6.30*)	77.51 (*129.18*)	48.73 (*81.22*)	43.72 (*72.88*)	43.09 (*71.82*)

Crop	**Chippies Field – Winter wheat 2009-10 [Plot size =6 m^2]**					
Application rate (kg [N] ha^{-1})	**Biosolids**		**OMF_{10}**		**OMF_{15}**	
	$[P_2O_5]$	**$[K_2O]$**	**$[P_2O_5]$**	**$[K_2O]$**	**$[P_2O_5]$**	**$[K_2O]$**
0	-	-	-	-	-	-
50	23.65 (*39.42*)	1.09 (*1.82*)	17.50 (*29.17*)	10.03 (*16.72*)	9.35 (*15.58*)	7.45 (*12.42*)
100	47.30 (*78.83*)	2.19 (*3.65*)	34.99 (*58.32*)	20.06 (*33.43*)	18.70 (*31.17*)	14.91 (*24.85*)
150	70.95 (*118.25*)	3.28 (*5.47*)	52.49 (*87.48*)	30.08 (*50.13*)	28.05 (*46.75*)	22.36 (*37.27*)
200	94.60 (*157.67*)	4.38 (*7.30*)	69.99 (*116.65*)	40.11 (*66.85*)	37.40 (*62.33*)	29.82 (*49.70*)
250	118.25 (*197.08*)	5.47 (*9.12*)	87.48 (*145.80*)	50.14 (*83.57*)	46.75 (*77.92*)	37.27 (*62.12*)

Appendix A.7.4: Plot combine harvester

Figure A.7.6: Plot combine harvester Deutz-Fahr M660 used in the field experiments (left) and close-up of the bagging device (right).

Appendix A.7.5: Statistical analyses corresponding to Chapter 7: Field studies

The statistical analyses can be found in the CD enclosed in the following folder:

- EngD Thesis\Appendices\Appendix Chapter 7 Field studies

Appendix A.7.6: Regression analysis – harvest index versus nitrogen application rate for winter wheat 2007-08 & 2008-09

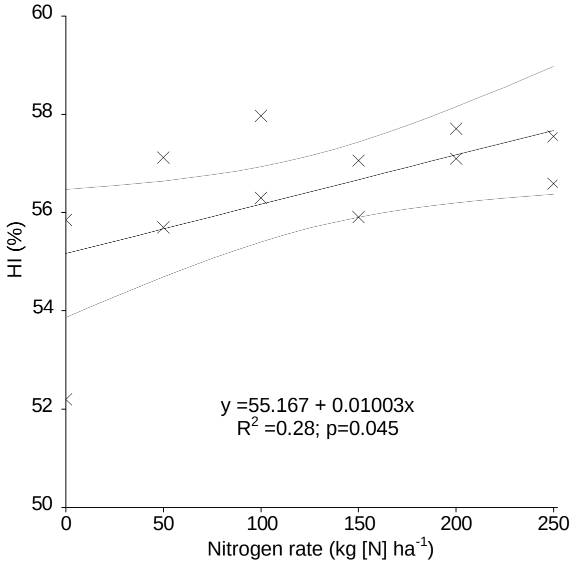


Figure A.7.7: Relationship between nitrogen application rate and harvest index (HI, %) corresponding to the harvest seasons of 2007-08 and 2008-09. The curves up and above the fitted curve represent the 95% confidence interval (n=12 except control n=4 and plots treated with 250 kg [N] ha^{-1} n=8).

Appendix A.7.7: Dry matter yield of rye grass and crop responses to applied fertiliser – Analysis of data corresponding to individual cuts in 2009 and 2010 – Field studies

Overall, in 2009 (**Figure A.7.7**) the results showed significant differences in production of dry matter between the control and the treatments (p<0.001). There were also significant differences in production of dry matter with respect to the fertiliser type and the nitrogen application rate used (p values <0.001). However, the interaction between nitrogen application rate and the fertiliser type did not show a significant effect upon the yield of the grass (p=0.896). When factoring in the time, a significant effect (p<0.001) was observed which indicated that the production of dry matter differed significantly between the cuts and the same was observed for both the fertiliser type and the nitrogen application rate used with respect to the time (p-values <0.001). This indicates that effect of the nitrogen application rate and the fertiliser type used produced, overall, a significant effect on the yield of the grass when considering individual cuts. The interaction between the fertiliser type and the nitrogen application rate with respect to the time did not show a significant effect (p=0.891).

In 2010 (**Figure A.7.8**), the control plots produced overall significantly lower level of dry matter compared with treated plots (p<0.001) and the same overall effect was observed with respect to the fertiliser type and the nitrogen rate used (p values <0.001). The interaction between the fertiliser type and the nitrogen application rate showed overall no significant effect (p=0.927). In addition, when there was a significant effect with respect to the time which indicates that the amount of dry matter produced overall in each cut differed significantly (p<0.001) and the same was observed when comparing the control and the treatments with respect to the time (p=0.017) and with respect to the fertiliser type and the nitrogen application rate (p values <0.001). As highlighted for 2009, the interaction between the fertiliser type and the nitrogen application rate with respect to the time did not show a significant effect (p=0.825).

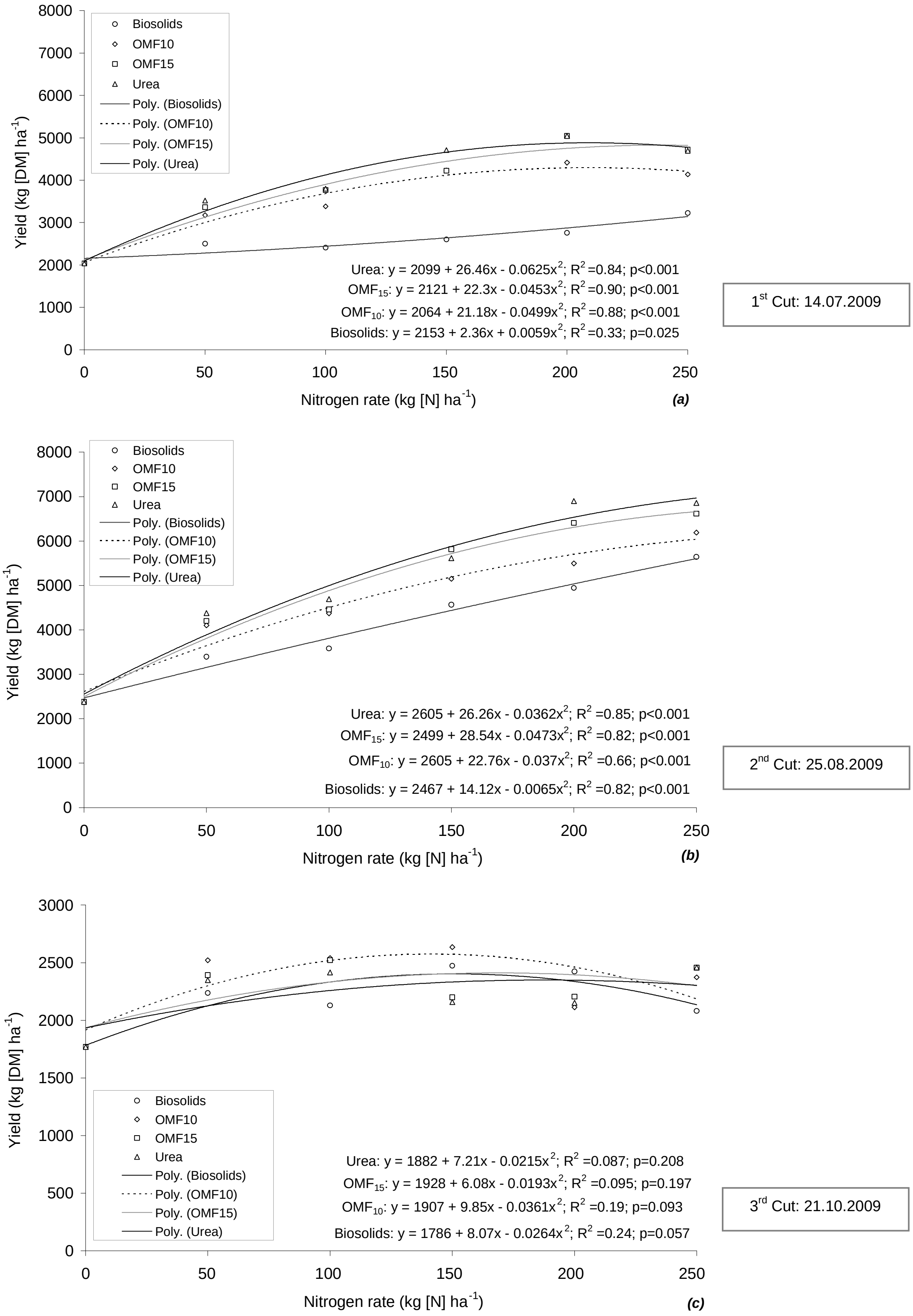


Figure A.7.8: Response of rye-grass to applied fertiliser and biosolids in Avenue Field for the (*a*) first, (*b*) second and (*c*) third cuts conducted in 2009 [$\text{LSD}_{[5\%\ \text{level}]}$ =645.6 (min.rep); $\text{LSD}_{[5\%\ \text{level}]}$ =589.3 (max-min. rep); $\text{LSD}_{[5\%\ \text{level}]}$ =527.1 (max.rep); n=3 except control n=4 and plots treated with 250 kg [N] ha^{-1} n=2].

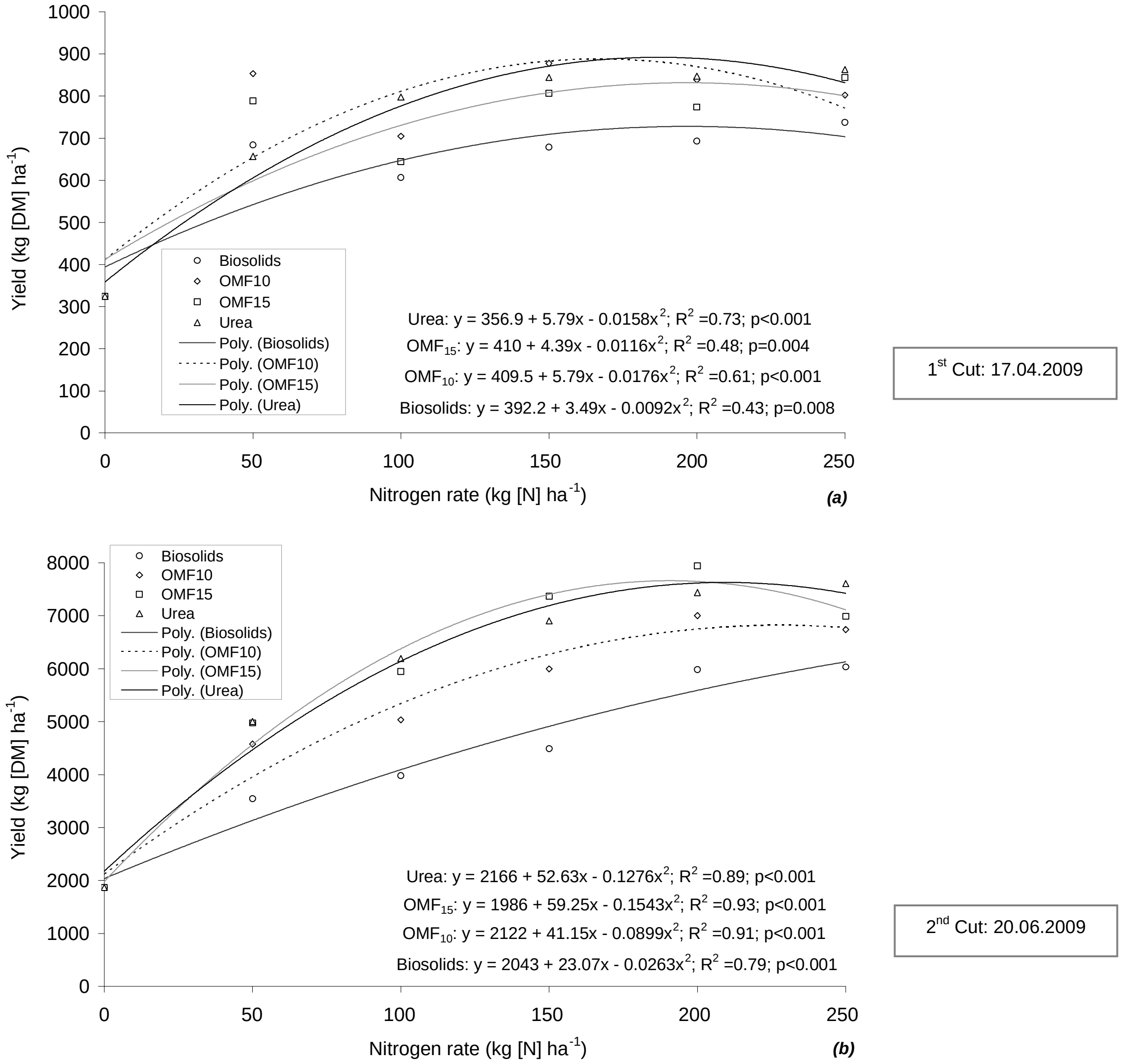


Figure A.7.9: Response of rye-grass to applied fertiliser and biosolids in Avenue Field for the (*a*) first and (*b*) second cuts conducted in 2010. [LSD$_{[5\%\ \text{level}]}$ =786.5 (min.rep); LSD$_{[5\%\ \text{level}]}$ =718.0 (max-min. rep); LSD$_{[5\%\ \text{level}]}$ =642.2 (max.rep); n=3 except control n=4 and plots treated with 250 kg [N] ha^{-1} n=2].

APPENDIX CHAPTER 8

Appendix A.8.1: Gross margin analyses

Notation:

- *a*, *b*, and *c*: regression coefficients from response functions,
- P_N: price of the nitrogen,
- P_C: price of the crop,
- R_P: price ratio; i.e. the ratio price of the nitrogen to price of the crop,
- MERN: the most economic rate of nitrogen application,
- Y_{MERN}: grain yield corresponding to MERN,
- GI: gross income,
- Application Eq./dressing: number of applications equivalent per dressing (see **Equation [8.10]**).
- Cost of spreading (broadcast): Cont'r (contractor's charge) and Farmer (farmer's cost of spreading).

A.8.1.1: Estimation of MERN, Y_{MERN} and gross income

2006-07	**Regression coefficients**			P_N	P_C	R_P	**MERN**	Y_{MERN}	**GI**
Fertiliser	***a***	***b***	***c***	**(£ kg^{-1})**	**(£ kg^{-1})**	---	**(kg ha^{-1})**	**(kg ha^{-1})**	**(£ ha^{-1})**
Biosolids	6326	37.40	-0.0792	0.00	0.099	0.00	235.9	10734	1062.67
OMF_{10}	6437	26.87	-0.0412	0.424	0.099	4.28	274.1	10707	1059.99
OMF_{15}	6366	31.15	-0.0541	0.424	0.099	4.28	248.3	10765	1065.74
Urea	6456	35.69	-0.0692	0.424	0.099	4.28	226.9	10992	1088.21

2007-08	**Regression coefficients**			P_N	P_C	R_P	**MERN**	Y_{MERN}	**GI**
Fertiliser	***a***	***b***	***c***	**(£ kg^{-1})**	**(£ kg^{-1})**	---	**(kg ha^{-1})**	**(kg ha^{-1})**	**(£ ha^{-1})**
Biosolids	2876	30.05	-0.0497	0.00	0.127	0.00	302.3	7418	942.09
OMF_{10}	3827	42.70	-0.1039	1.043	0.127	8.22	165.9	8052	1022.60
OMF_{15}	3384	36.00	-0.0730	1.043	0.127	8.22	190.3	7591	964.06
Urea	3087	56.90	-0.1231	1.043	0.127	8.22	197.7	9525	1209.68

2008-09	**Regression coefficients**			P_N	P_C	R_P	**MERN**	Y_{MERN}	**GI**
Fertiliser	***a***	***b***	***c***	**(£ kg^{-1})**	**(£ kg^{-1})**	---	**(kg ha^{-1})**	**(kg ha^{-1})**	**(£ ha^{-1})**
Biosolids	5102	50.80	-0.1398	0.00	0.108	0.00	181.7	9717	1049.44
OMF_{10}	5055	44.76	-0.0903	0.50	0.108	4.63	222.2	10542	1138.54
OMF_{15}	4212	71.96	-0.1580	0.50	0.108	4.63	213.1	12372	1336.18
Urea	4701	70.00	-0.1483	0.50	0.108	4.63	220.4	12925	1395.90

2009-10	**Regression coefficients**			P_N	P_C	R_P	**MERN**	Y_{MERN}	**GI**
Fertiliser	***a***	***b***	***c***	**(£ kg^{-1})**	**(£ kg^{-1})**	---	**(kg ha^{-1})**	**(kg ha^{-1})**	**(£ ha^{-1})**
Biosolids	849	21.83	-0.0409	0.00	0.127	0.00	266.9	3762	477.77
OMF_{10}	960	28.38	-0.0319	0.624	0.127	4.92	367.7	7083	899.54
OMF_{15}	956	31.65	-0.0390	0.624	0.127	4.92	342.7	7222	917.19
Urea	1145	48.06	-0.0840	0.624	0.127	4.92	256.8	7947	1009.27

A.8.1.2: Variable costs – cost of fertiliser and fertiliser spreading

Table A.8.1: Contract charge and farmer's cost of broadcast spreading (£ ha^{-1}) between 2006-07 and 2009-10 (source: Nix, 2007-10).

Broadcast spreading range (kg ha^{-1})	**2006-07**		**2007-08**		**2008-09**		**2009-10**	
	Cont'r	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**	**Cont'r**	**Farmer**
	-- £ ha^{-1} --							
125-375	10.25	6.40	10.10	7.80	10.25	7.30	9.75	7.80
500-750	16.16	10.10	16.32	12.60	16.29	11.60	15.63	12.50
1000-1250	24.32	15.20	24.61	19.00	24.43	17.40	23.50	18.80

2006-07	**Rate@MERN**	**Rate/dressing**	**Application**	**Cost of N**	**Cost spreading (£ ha^{-1})**	
Fertiliser	**(kg [product] ha^{-1})**	**(kg [product] ha^{-1})**	**Eq./dressing**	****(£ ha^{-1})**	**Cont'r**	**Farmer**
Biosolids	6064.3	3032.1	2.43	50	117.99	73.74
OMF_{10}	3371.5	1685.7	1.35	165.12	65.60	41.00
OMF_{15}	2525.9	1263.0	1.01	154.29	49.14	30.72
Urea	493.3	246.6	1.00	145.30	20.50	12.80

**Cost of nitrogen includes the cost of UAN (33% N - solution) at a rate of 100 kg [N] ha^{-1} and the field spreading estimated at £50 per hectare.

2007-08	**Rate@MERN**	**Rate/dressing**	**Application**	**Cost of N**	**Cost spreading (£ ha^{-1})**	
Fertiliser	**(kg [product] ha^{-1})**	**(kg [product] ha^{-1})**	**Eq./dressing**	**(£ ha^{-1})**	**Cont'r**	**Farmer**
Biosolids	6673.3	3336.6	2.67	0.00	131.36	101.43
OMF_{10}	1577.0	788.5	1.05	173.03	34.32	26.49
OMF_{15}	1185.7	592.8	1.00	198.48	32.64	25.20
Urea	429.8	214.9	1.00	206.20	20.20	15.60

2008-09	**Rate@MERN**	**Rate/dressing**	**Application**	**Cost of N**	**Cost spreading (£ ha^{-1})**	
Fertiliser	**(kg [product] ha^{-1})**	**(kg [product] ha^{-1})**	**Eq./dressing**	**(£ ha^{-1})**	**Cont'r**	**Farmer**
Biosolids	4576.8	2288.4	1.83	0.00	89.45	63.71
OMF_{10}	2255.8	1127.9	1.00	111.10	48.86	34.80
OMF_{15}	1526.5	763.3	1.02	106.55	33.15	23.61
Urea	479.1	239.6	1.00	110.20	20.50	14.60

2009-10	**Rate@MERN**	**Rate/dressing**	**Application**	**Cost of N**	**Cost spreading (£ ha^{-1})**	
Fertiliser	**(kg [product] ha^{-1})**	**(kg [product] ha^{-1})**	**Eq./dressing**	**(£ ha^{-1})**	**Cont'r**	**Farmer**
Biosolids	4870.4	2435.2	1.95	0.00	91.56	73.25
OMF_{10}	5142.7	2571.3	2.06	229.44	96.68	77.35
OMF_{15}	3008.8	1504.4	1.20	213.84	56.57	45.25
Urea	558.3	279.1	1.00	160.24	19.50	15.60

Appendix A.8.2: Pilot choice experiment – First questionnaire using two levels and three attributes

QUESTION # 1		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	15
Phosphorus (% P_2O_5) content	0	4
Price per tonne (£/tonne product)	480	125
Which product would you choose?		

QUESTION # 2		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	15
Phosphorus (% P_2O_5) content	0	4
Price per tonne (£/tonne product)	480	110
Which product would you choose?		

QUESTION # 3		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	15
Phosphorus (% P_2O_5) content	0	8
Price per tonne (£/tonne product)	480	125
Which product would you choose?		

QUESTION # 4		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	15
Phosphorus (% P_2O_5) content	0	8
Price per tonne (£/tonne product)	480	110
Which product would you choose?		

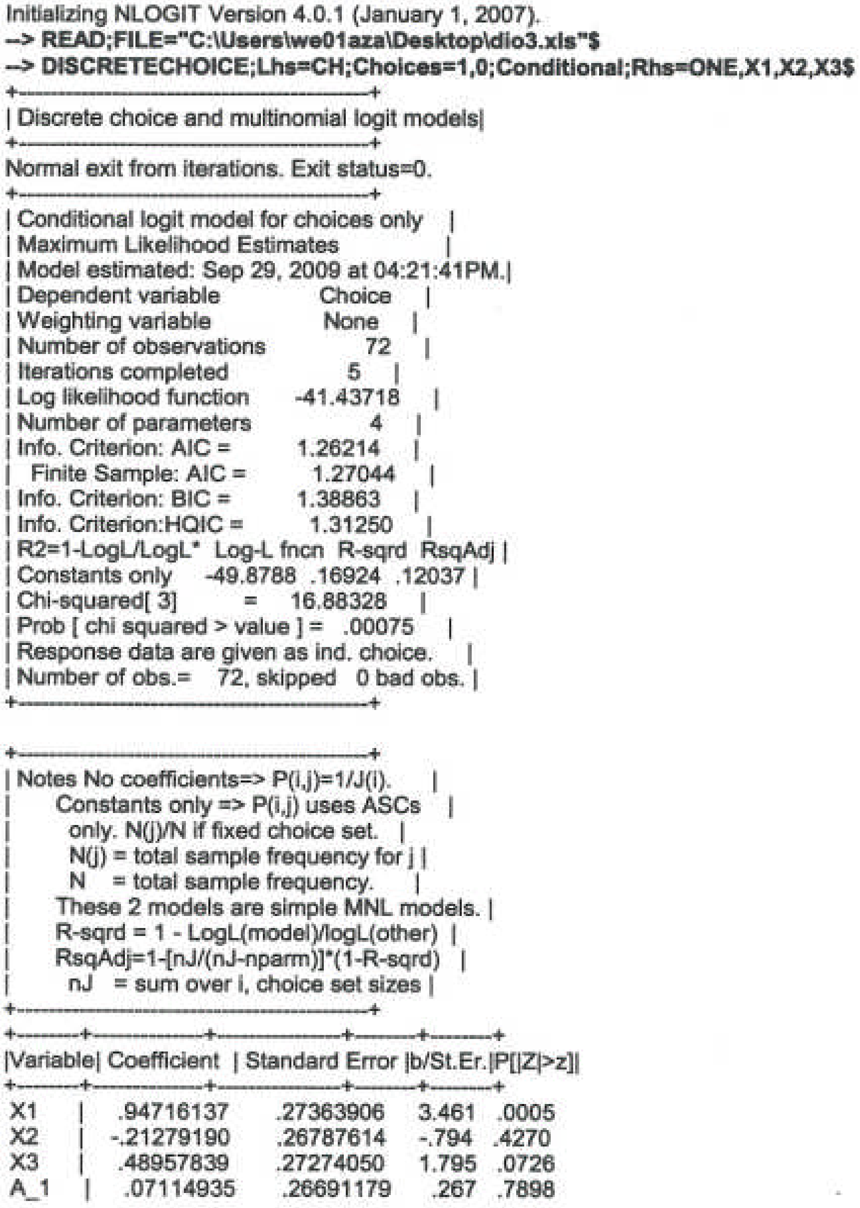
QUESTION # 5		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	10
Phosphorus (% P_2O_5) content	0	4
Price per tonne (£/tonne product)	480	125
Which product would you choose?		

QUESTION # 6		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	10
Phosphorus (% P_2O_5) content	0	4
Price per tonne (£/tonne product)	480	110
Which product would you choose?		

QUESTION # 7		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	10
Phosphorus (% P_2O_5) content	0	8
Price per tonne (£/tonne product)	480	125
Which product would you choose?		

QUESTION # 8		
Fertiliser Characteristics	**Current Product**	**New Product**
Nitrogen content (%)	46	10
Phosphorus (% P_2O_5) content	0	8
Price per tonne (£/tonne product)	480	110
Which product would you choose?		

Appendix A.8.3: NLogit output of statistical analysis of the pilot choice experiment for two levels and three attributes



```
Initializing NLOGIT Version 4.0.1 (January 1, 2007).
--> READ;FILE="C:\Users\we01aza\Desktop\dio3.xls"$
--> DISCRETECHOICE;Lhs=CH;Choices=1,0;Conditional;Rhs=ONE,X1,X2,X3$
+---------------------------------------------+
| Discrete choice and multinomial logit models|
+---------------------------------------------+
Normal exit from iterations. Exit status=0.
+---------------------------------------------+
| Conditional logit model for choices only    |
| Maximum Likelihood Estimates                |
| Model estimated: Sep 29, 2009 at 04:21:41PM.|
| Dependent variable               Choice     |
| Weighting variable                None      |
| Number of observations              72      |
| Iterations completed                 5      |
| Log likelihood function      -41.43718      |
| Number of parameters                 4      |
| Info. Criterion: AIC =         1.26214      |
|   Finite Sample: AIC =         1.27044      |
| Info. Criterion: BIC =         1.38863      |
| Info. Criterion:HQIC =         1.31250      |
| R2=1-LogL/LogL*  Log-L fncn  R-sqrd  RsqAdj |
| Constants only    -49.8788  .16924  .12037 |
| Chi-squared[ 3]          =     16.88328     |
| Prob [ chi squared > value ] =   .00075     |
| Response data are given as ind. choice.     |
| Number of obs.=    72, skipped   0 bad obs. |
+---------------------------------------------+

+---------------------------------------------+
| Notes No coefficients=> P(i,j)=1/J(i).      |
|       Constants only => P(i,j) uses ASCs    |
|         only. N(j)/N if fixed choice set.   |
|         N(j) = total sample frequency for j |
|         N    = total sample frequency.      |
|       These 2 models are simple MNL models. |
|       R-sqrd = 1 - LogL(model)/logL(other)  |
|       RsqAdj=1-[nJ/(nJ-nparm)]*(1-R-sqrd)   |
|         nJ   = sum over i, choice set sizes |
+---------------------------------------------+
+--------+--------------+----------------+--------+--------+
|Variable| Coefficient  | Standard Error |b/St.Er.|P[|Z|>z]|
+--------+--------------+----------------+--------+--------+
 X1      |   .94716137      .27363906     3.461   .0005
 X2      |  -.21279190      .26787614     -.794   .4270
 X3      |   .48957839      .27274050     1.795   .0726
 A_1     |   .07114935      .26691179      .267   .7898
```

Appendix A.8.4: Pilot Choice Experiment – Respondents' views of the first questionnaire using two levels and three attributes

Respondent 1:
It depends on the results of my soil analysis; I would probably opt for OMF. However, I'm not convinced you would be able to get the willingness to pay from this analysis, am I wrong?

Respondent 2:
I found it difficult to answer. Firstly, because the numbers are not easy multiples, I needed a calculator out to answer them. It all seems very technical/simultaneous equation type of questions. The key question is the overhead costs for applying the fertiliser per kg *vs.* the cost of the fertiliser. Surely the stated aim of the farmer is important; some local farmers here are not interested in applying K because of the high K content of soils.

Respondent 3:
Would have thought questions with wider 100, 110, 120 price;
Quality of the prill would be an important attribute;
Is it liquid or solid?
How much of the total-N is ammonia-N?

Respondent 4:
Your new product works out cheaper and with some phosphorus (% P_2O_5) content, is a bonus. The downside would be the amount of product you would have to apply to get the same amount of N. This would incur cost of spreading, time to spread which at a busy time of year (spray wise) would put pressure on the farmer to cover the hectares, and the availability of good spreading days.

Respondent 5:
Mine is attached. As a farmer, my main concern is the economical benefit that I can get by using this fertiliser. If I am not convinced about its performance then I would not gamble on my money. But when I get considerable margin compared to the current product I would consider trying it. Let me put some of the things that came to my mind when I was filling this in:

a. 46% N or urea is not something many farmers use in the UK (urea represents *c.*15% of the UK nitrogen fertiliser usage). Would this comparison be very hypothetical for a farmer who is not very familiar to urea and OMF? What if we use AN instead of urea?

b. Also, you've got P levels that we cannot achieve or planning to achieve in the future. I presume with those suggestions, you try to understand whether P level in the OMF would affect buyers' decision.

c. Your OMF_{10} formulation is priced "high" compared with the OMF_{15} formulation. If I was a farmer, I would be concerned of the cost of application on top of the price when it comes to a low concentrated fertiliser product. In that case, there is no chance for OMF_{10} based on your suggested prices.

Respondent 6:
Is it N content *vs.* cost with the additional P benefit? Would I not be making these decisions based upon whether I needed the P or not?

Respondent 7:
My reply is attached. My only uncertainty is that I have to put on 3 plus times as much new product. How much will this cost in extra storage and spreading cost. I still think it will be OK but that needs investigation.

Respondent 8:
I have used very simplistic criteria. I would not be prepared to pay as much for something that is less well understood. I am ignorant of the value of the P. If P doesn't mineralise much then is it P content relevant. Or in fact is P a risk? So in simple terms I would be prepared to pay for the N but it would have to be at a lower value than mineral N because of a range of perceived risks in using the novel product.

Respondent 9:
Current price of ammonium nitrate is £190 with this in mind I would choose this. The trouble with super pooh is that you need to apply such large quantities to achieve the same ratios. Anglia Water is charging £25 tonne spread at present. I find it very difficult to compare the two products as one is straight and one is not. Sorry to be negative!

Respondent 10:
Use a facts sheet providing information on OMF products/technology. Use a range of values for each one of the attributes used and give them in percentages to facilitate any comparison with the standard NPK fertiliser.

Appendix A.8.5: Pilot choice experiment – Second questionnaire using two levels and four attributes

QUESTION # 1		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	92
Which product would you choose?		

QUESTION # 2		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	112
Which product would you choose?		

QUESTION # 3		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	97
Which product would you choose?		

QUESTION # 4		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	117
Which product would you choose?		

QUESTION # 5		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	97
Which product would you choose?		

QUESTION # 6		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	117
Which product would you choose?		

QUESTION # 7		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	102
Which product would you choose?		

QUESTION # 8		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	122
Which product would you choose?		

QUESTION # 9		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	90
Which product would you choose?		

QUESTION # 10		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	110
Which product would you choose?		

QUESTION # 11		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	95
Which product would you choose?		

QUESTION # 12		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	4
Price per tonne (£/tonne product)	220	115
Which product would you choose?		

QUESTION # 13		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	95
Which product would you choose?		

QUESTION # 14		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	4
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	115
Which product would you choose?		

QUESTION # 15		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	10
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	100
Which product would you choose?		

QUESTION # 16		
Fertiliser Characteristics	**Product A**	**Product B**
Nitrogen content (%)	20	15
Phosphorus (% P_2O_5) content	10	8
Potassium (% K_2O) content	10	8
Price per tonne (£/tonne product)	220	120
Which product would you choose?		