The physiological basis and consequences for nitrate leaching of novel fertiliser strategies involving foliar fertilisation of wheat

Thesis

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THE PHYSIOLOGICAL BASIS AND CONSEQUENCES FOR NITRATE LEACHING OF NOVEL FERTILISER STRATEGIES INVOLVING FOLIAR FERTILISATION OF WHEAT

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The physiological basis and consequences for nitrate leaching of novel fertiliser strategies involving foliar fertilisation of wheat.

by R.J. Readman

Abstract

Supplying a proportion of the N requirement of a wheat crop via the foliage would potentially reduce immobilisation of fertiliser N in the soil organic matter and losses by leaching or denitrification.

A field experiment to investigate the effects on crop yield, N recovery and nitrate leaching of supplying the main spring N application to winter wheat as different proportions of foliar urea rather than as soil applied ammonium nitrate was repeated on the same site over three years. In year two, for selected treatments in the main experiment, recovery of ^{15}N-labelled nitrogen in the plant and soil was recorded. Experiments were conducted to investigate interception by the foliage, and the effect of timing and rate of N applied.

N as foliar urea produced similar yields to N applied conventionally to the soil as solid ammonium nitrate or urea over a range of rates of N applied. Early application of foliar urea increased above ground dry matter production and had little effect on harvest index, later applications reduced above ground dry matter production and increased harvest index. The effect of foliar urea on above ground dry matter production was due to increased green area index at anthesis, owing to increased leaf expansion.

Apparent recoveries indicated that gaseous losses, most likely by volatilisation, can be important for high rates of N applied as foliar urea under warm windy conditions. Applied under cooler conditions likely to inhibit gaseous losses however, true recovery of fertiliser N in the crop-soil system was similar to that for N applied to the soil as solid ammonium nitrate or urea.

N leaching losses were elevated for all treatments in all years. Application of N as foliar urea under conditions conducive to gaseous losses reduced nitrate leaching, due to increased C/N ratio of incorporated plant residues increasing immobilisation of mineral N.

Exploiting the potential for increased physiological N use efficiency as indicated and controlling gaseous losses would potentially reduce N losses.

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- Alison for putting up with it.

Statement of Advanced Studies

During the tenure of this project, in addition to carrying out and reporting the work described in this thesis the author has also:

- completed a programme of guided reading
- completed a basic course in statistical methods
- completed a Genstat 5 Introductory Course
- completed a Certificate of Competence in the use of pesticides
- attended and presented work at a number of seminars at Harper Adams Agricultural College
- attended a number of relevant conferences:-

  International Conference of the Fertiliser Society. 'Fertilisers in the European Environment'. Robinson College Cambridge, 1992.

  Association of Applied Biologists with the Royal Society and the Society of Chemical Industry. 'Novel Aspects of Crop Nutrition'. Harper Adams Agricultural College, Shropshire, 1993.

  Association of Applied Biologists. 'Physiology of Varieties'. Nottingham University, 1993.

  3rd Wye International Conference on Sustainable Agriculture. 'Soil Management in Sustainable Agriculture'. Wye College, 1993 (Spoken paper).

  Association of Applied Biologists. 'Cereal Quality III'. Churchill College Cambridge, 1993

  The 48th Oxford Farming Conference. 'Turning Threats into Opportunities'. Oxford University, 1994.

  Society for Experimental Biology. 'Annual Meeting'. St. Andrews, 1995 (Poster presented).

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1.0 INTRODUCTION

1.1 Background to the Project

About 0.35 million tonnes of fertiliser N are applied to winter wheat in the UK each year (calculated from Chalmers *et al.*, 1995); of this between 10 and 60% is not recovered by the crop (Bloom *et al.*, 1988). Losses of nitrogen from agriculture contribute to environmental and health problems and represent a waste of valuable resources. Gaseous losses as nitrous oxide, due to denitrification, contribute to global warming and cause depletion of the ozone layer (Addiscott *et al.*, 1991), while losses as ammonia due to volatilisation contribute to soil acidification when it returns to the land in rain water (Holtan-Hartwig and Bockman, 1994). That leached as nitrate can enter potable and surface waters where it has been associated with eutrophication and implicated in human health issues, notably methaemoglobinaemia ("blue baby syndrome") and stomach cancer, though the latter is by no means proven (Addiscott *et al.*, 1991). Environmental and health concerns over the level of nitrate in water led to the adoption by member states in 1980 of the EC Directive on the quality of water intended for human consumption (Council of the European Communities, 1980), which set a maximum allowable concentration of 50 mg/l of nitrate in drinking water. An increasing number of water sources exceed this concentration (MAFF, 1993) and in December 1991, member states adopted the European Community Nitrate Directive (Council of the European Communities, 1991). This directive extends the 50 mg/l limit to all surface and ground waters. It requires restrictions on agriculture in the catchment areas of water which exceed the 50 mg/l limit, or are at risk of doing so in the future.

In addition to the environmental and health concerns, increased pressure on farm profitability in recent years, particularly in the arable sector, has placed renewed emphasis on the efficient use of inputs to reduce costs of production. The efficient use of nitrogen fertiliser is therefore paramount in this respect.

The environmental problems and economic implications associated with losses of nitrogen from the plant-soil system have been instrumental in stimulating attempts to improve efficiency of nitrogen utilisation. Cereals occupy 65% of arable land in the UK (MAFF, 1994a) and are grown on a large scale in North Western Europe. Efficiency of nitrogen utilisation of cereals is therefore particularly important.

Foliar application of urea to winter wheat is currently practised as a late season supplement to basal N to increase grain protein content (Pushman & Bingham, 1976; Penny *et al.*, 1983; Rule, 1987; Gooding *et al.*, 1991). Theoretically, it would be possible to supply a large proportion of the total nitrogen requirement of a wheat crop via the foliage. This would potentially reduce immobilisation of fertiliser nitrogen in the soil organic matter and losses by leaching or denitrification (Powlson *et al.*, 1989a; Poulton *et al.*, 1990). Possible additional benefits may arise from foliar applied nitrogen being less dependent on soil conditions for assimilation (Currie, 1988; Powlson *et al.*, 1987a) and reduced incidence of foliar diseases (Gooding *et al.*, 1988).

Application of nitrogen as foliar urea, must at least maintain yield. The timing of applications in relation to the development of the leaf canopy and yield components is likely to be critical in this context. The yield reduction with foliar urea reported by others (Poulton *et al.*, 1990) may have resulted from reduced effectiveness due to late application.

The aim of this project was to investigate the physiological consequences of foliar urea applications and effects on nitrate leaching as a basis for rational development of a more environmentally acceptable method of nitrogen fertiliser application to winter wheat.

The objectives of this project were therefore:

i) To conduct a review of the literature in order to understand what other people have done in this field and to outline the current state of knowledge regarding the subject area.

ii) To set up a field experiment (the "main experiment") to be repeated on the same site over three years to compare supplying the main spring nitrogen application as different proportions of foliar urea rather than as conventional soil applied ammonium nitrate or urea.

iii) To study tiller, leaf canopy and ear development to relate these to yield.

iv) To measure apparent recovery of fertiliser N in the above ground crop and to measure soil water nitrate concentrations over the following winter to estimate nitrate leaching.

v) To develop further experiments as necessary alongside the main experiment, to investigate questions arising and hypotheses developed from the findings of the main experiment.

1.2 Structure of the Thesis

The literature review is presented first (Chapter 2). N in the soil is considered first; sources of N in the soil, the fate of fertiliser N and specifically nitrate leaching are reviewed. Nitrogen in crop production is then considered and specifically work relating to foliar N. The main experiment is then reported (Chapter 3). Experimental method, results and discussion are presented for each of the three years, 1992-1994. The further experiments developed from the findings of the main experiment are then reported (Chapters 4 to 7). As for the main experiment, experimental method, results and discussion are presented for each experiment. The main points arising from each of the experiments are then brought together in the general discussion and conclusion. Finally, suggestions are made for further work.

2.0 REVIEW OF THE LITERATURE

2.1 Objectives of the Review

The aim of this project as stated, was to investigate the physiological consequences of foliar urea applications and effects on nitrate leaching as a basis for rational development of a more environmentally acceptable method of nitrogen fertiliser application to winter wheat.

With respect to the consequences for nitrate leaching, an understanding of the factors affecting nitrate levels in the soil and the current state of knowledge regarding N losses by this pathway is required. Nitrate leaching, however, only represents one pathway for N losses from the plant-soil system. Due to the application of N as foliar urea, other N loss pathways may be important. Recovery of fertiliser N by the crop and fertiliser N remaining in the soil, are important factors influencing (potential) losses of fertiliser N from the plant-soil system. A knowledge of recovery of N in the plant-soil system as reported elsewhere is therefore important.

With respect to the physiological basis of the effect of foliar urea on yield, an essential prerequisite is an understanding of the effect of conventional N applications on the components of yield. A knowledge of the effect of foliar urea in this context as reported by others is also required. The pathway for uptake of N applied to the foliage is very different to that for N applied to the soil. Differences in the pathway and mechanism of uptake may be important with respect to the physiological effects and losses of N applied as foliar urea. An understanding of the pathway and mechanism of uptake for N applied as foliar urea is therefore desirable. Finally, a prerequisite of any study investigating novel fertiliser strategies is a knowledge of conventional fertiliser recommendation systems currently employed.

The objectives of this review are therefore:

i) With respect to nitrogen in the soil:

- to outline sources of nitrogen available to the plant and the fate of fertiliser nitrogen,
- to review the literature regarding nitrate leaching, with particular reference to factors affecting and methods of measuring nitrate leaching,
- to review the literature regarding recovery of nitrogen in the plant-soil system with particular reference to foliar applied nitrogen.

ii) With respect to nitrogen in the plant:

- to outline current theory regarding the physiological basis of the effect of nitrogen on the yield of wheat and to review the effect of foliar urea in this context,
- to outline the mechanism of uptake of foliar applied urea,
- to outline current recommendation systems used for the application of nitrogen.

2.2 Nitrogen in the Soil

2.2.1 Sources of Nitrogen Available for Loss

i) Natural Sources

Figure 2.1 shows the nitrogen cycle in the UK and the interaction between atmospheric, aquatic and terrestrial ecosystems. The organic matter in the soil comprising crop residues and microbial biomass, constitutes an important reservoir of nitrogen. On a global basis it represents the third largest repository of nitrogen on the planet (Table 2.1). A soil that has been under cultivation for a long period and therefore has a relatively small organic matter content will contain 2000-3000 kg N/ha, mainly in organic forms and mostly in the plough layer. More typically, arable soils will contain 3000-5000 kg N/ha (Addiscott *et al.*, 1991).

Table 2.1 Estimates of active pools in the global nitrogen cycle (adapted from Jenkinson, 1990)

Nitrogen	Tonnes	
The atmosphere	3.9×10^{15}	
Sea (various)	2.4×10^{13}	
Soil organic matter (non living)	1.44×10^{11}	} 1.5×10^{11}
Microbes in soil	6.0×10^{9}	
Plants (land)	1.5×10^{10}	
Animals (land)	1.9×10^{8}	
People	1.0×10^{7}	

Despite its magnitude, the organic nitrogen pool in the soil is relatively inert, and is not directly available for loss. Before organic N is "available" for plant uptake or loss it has to be processed by mineralisation. This is the process by which carbon compounds are degraded by soil

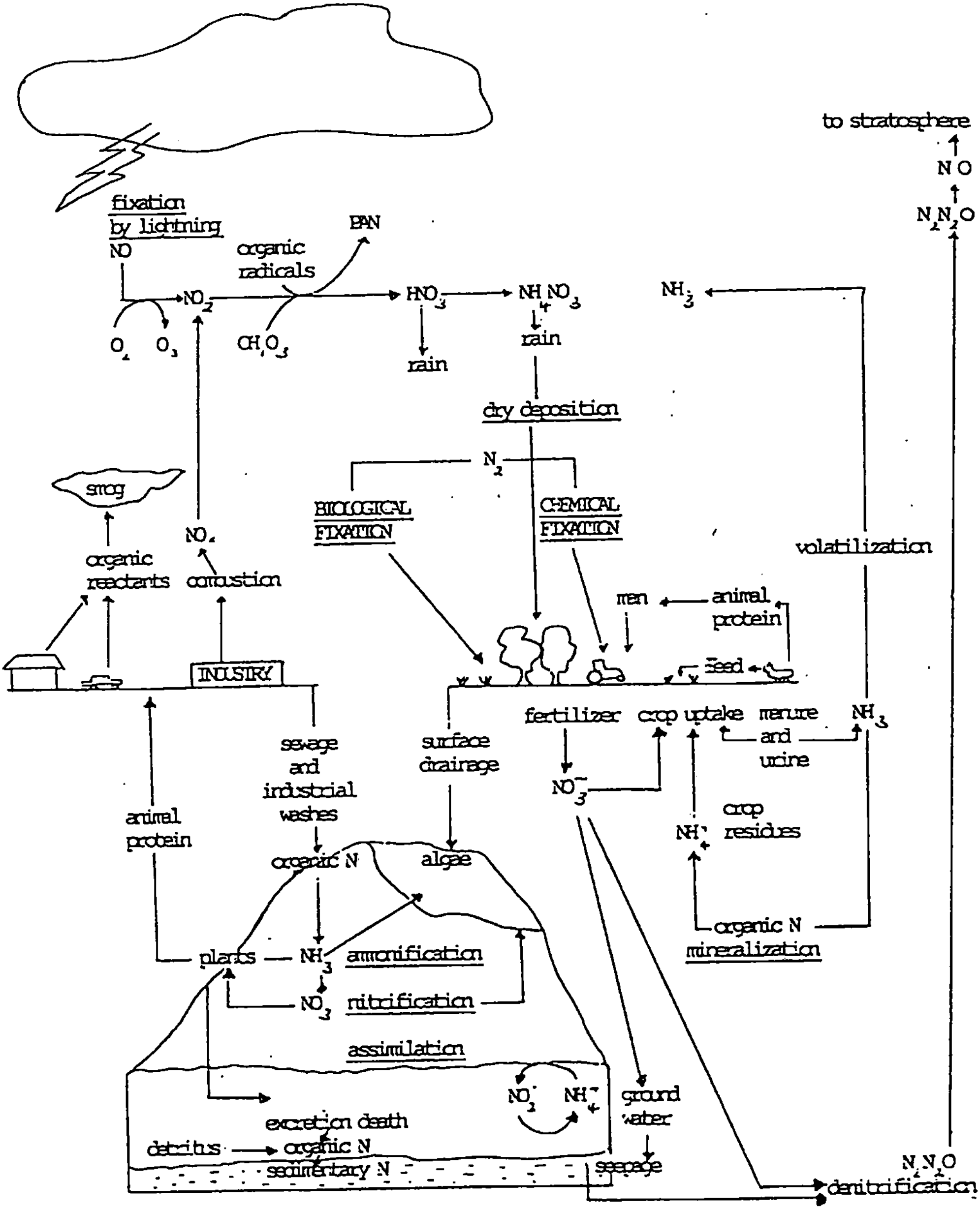


Figure 2.1 The UK nitrogen cycle (The Royal Society, 1983).

microbes and used as an energy source, nitrogen being necessary for the manufacture of certain essential molecules. Any excess C or N is returned in a chemically altered form to the humus, or liberated as simple non organic waste products; carbon as CO_2 and nitrogen as ammonium. With the exception of very acid or permanently waterlogged soils, the ammonium is then further oxidised by microbes, first to nitrite and then to nitrate, the final product of mineralisation. The first step in the mineralisation process, the conversion of organic N to ammonium, is called ammonification, while the conversion of ammonium to nitrate is called nitrification. A wide variety of bacteria and fungi are responsible for ammonification, while nitrification is a more specialised process involving principally *Nitrosomonas* and *Nitrobacter*.

A flush of nitrogen from this source occurs mainly in the autumn and spring, when the soil is warm and moist, favouring microbial activity (Figure 2.2). The contribution of mineralisation to available N in any year depends on the soil type, weather and probably the forms of organic N (Goulding and Poulton, 1992). Estimates are highly variable: Goulding and Poulton (1992) cite the general figure of less than 1 percent of the organic N per year (i.e. 30- 50 kg N/ha). Jenkinson (1986) notes that the heavier soils under cereals in eastern England often contain 60-120 kg N/ha as a result of mineralisation during the growing season, and Wehrmann *et al.*(1987) report figures of 32-185 kg N/ha. Powlson (1993) suggests that values of 30-100 kg N/ha as nitrate (to 1 m) due to mineralisation are common in arable soils in late summer. The latter figures reflect net mineralisation, i.e. gross mineralisation less gross immobilisation.

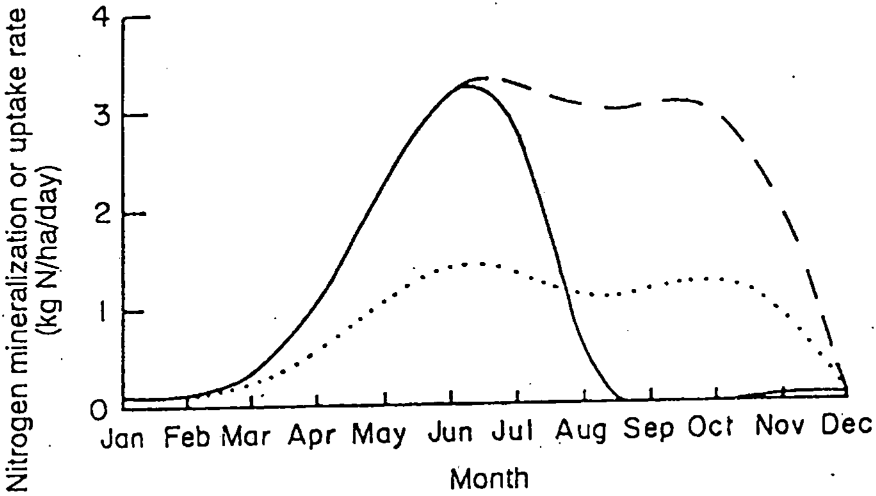


Figure 2.2 Time course of N mineralisation (....) and uptake by winter wheat (—) and grass (----) (after Powlson, 1993).

Nitrogen added to the land by dry deposition of particulate material and wet deposition of dissolved inorganic nitrogen in rainfall is another natural source of available N. Estimates of total deposition are highly variable, depending on location. Direct measurements at four sites in Eastern England (Goulding, 1990) and indirect estimates at Rothamsted (Jenkinson, 1982; Powlson *et al.*, 1986a), indicate an annual deposition to arable land in the order of 40 kg N/ha in this area.

Finally, the atmosphere consists of 78 percent free nitrogen which may be fixed biologically to form NH_3. Biological fixation is an important natural source of nitrate (via mineralisation) in farming systems where legumes are grown. On average, biological fixation has been estimated to contribute 5-10 kg N/ha/year to the total "atmospheric" input (Goulding, 1990).

The significance of these natural sources to nitrogen available for loss is shown by the Broadbalk experiment, where an area of arable land left bare and unmanured, on average leached 45 kg N/ha/year between 1854 and 1877 (Addiscott, 1988).

ii) Artificial Fertilisers

Fertiliser use in the UK has been reviewed by Chalmers *et al.* (1990). There was a five fold increase in use in the post war period 1953-74 (Church and Lewis, 1977) and applications continued to increase at a steady rate in the period 1975-83, to plateau at 180-200 kg N/ha for winter wheat. Approximately static results from 1983 to 1988 (Chalmers *et al.*, 1990; Figure 2.3) and subsequently (Chalmers *et al.*, 1995), suggest that the period of rapid expansion has come to an end.

Whatever form of nitrogen fertiliser is used, due to mineralisation, the usual end product in the soil that is available to plants is nitrate.

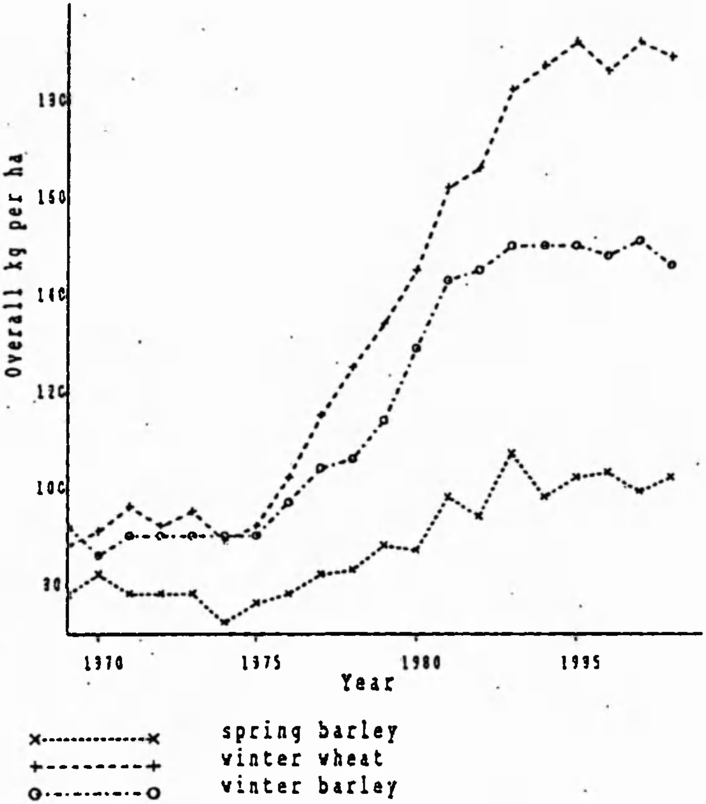


Figure 2.3 Use of N on spring barley, winter wheat, and winter barley (after Chalmers *et al.*, 1990).

2.2.2 The Fate of Fertiliser Nitrogen in the Soil

Having considered the sources of available N in the soil, the fate of this N is a question central to this thesis. In particular the fate of fertiliser derived N. There are five possibilities:

1. It may be incorporated into the soil organic matter by immobilisation.
2. It may undergo a process known as denitrification and be lost from the plant soil system as a gas.
3. It may be converted to ammonia and lost by volatilisation.
4. It may be lost as nitrate by leaching.
5. It may be recovered by the crop.

The objective of this study with respect to the fate of N is to assess the implications of applying fertiliser N as foliar urea rather than as solid soil applications with particular respect to the pathways of nitrate leaching and recovery by the crop, and it is these pathways that will be developed further in this review. As the pathways above are all interconnected, however, changing one changes the others. A broad appreciation of the other pathways, because of their implications for nitrate leaching and crop recovery is therefore necessary.

i) <u>Immobilisation</u>

The process of mineralisation by which organic N is converted to nitrate has been discussed. Immobilisation is the process running in the opposite direction. Soil microorganisms take up ammonium and nitrate during the decomposition of organic substrates and convert them into organic forms of nitrogen.

Whether immobilisation or mineralisation predominates when organic matter is added to the soil depends primarily on the nitrogen content of the organic matter. As a rule of thumb, material with a nitrogen content of less than 1.2 - 1.3 % (corresponding to a C/N ratio of about 30) will immobilise mineral N in the soil during the early weeks following addition. Material with more than 1.8 - 2 % N (corresponding to a C/N ratio of about 20) will mineralise nitrogen, usually within a week, if not immediately (Jenkinson, 1984).

Immobilisation of inorganic N can occur by chemical reactions (Mortland, 1958; Nelson and Bremner, 1969) or by physical restriction within mineral structures (Nommik, 1981). Such processes, however, are of little significance in mature top soils within the pH range 5 - 8.

Immobilisation and mineralisation can occur simultaneously, which process predominates depending on the amount and type of organic matter entering the soil. Consequently, changes in the mineral N pool due to these processes gives only net mineralisation or immobilisation, i.e. the difference between gross mineralisation and gross immobilisation.

ii) Denitrification

Denitrification is the process by which certain bacteria, under anaerobic conditions, strip the oxygen from nitrate to meet their oxygen requirement, liberating nitrogen and/or nitrous oxide to the atmosphere (equation 1). Denitrification tends to occur when soils become anaerobic due to wetness (but by no means saturated), water filled pores restricting the diffusion of oxygen, and are sufficiently warm for microbial activity (Fillery, 1983; Sahrawat and Keeney, 1986).

$$\begin{tikzcd} & & N_2O \\ NO_3^- \arrow[r] & NO_2^- \arrow[ur] \arrow[dr] & \\ & & N_2 \end{tikzcd} \qquad (1)$$

Denitrification tends to be highly variable, both in space (Parkin, 1987), and in time, occurring following rainfall or irrigation rather than continuously (Jarvis *et al.*, 1991). The rate of denitrification also obviously depends on the supply of nitrate, and is likely to be greatest when application of nitrogen fertilisers coincides with warm wet conditions. According to Addiscott *et al.* (1991), rates of denitrification in field soils are likely to be in the order of 3 kg N/ha/day.

While the existence of denitrification as a loss process has been appreciated for a long time (Allison, 1955); it is only recently that the importance of losses via this pathway have been appreciated. Denitrification losses are now thought to be the main source of loss of fertiliser N during the late spring, summer and early autumn (Jenkinson, 1986). Of the loss of fertiliser N applied to winter cereals on a range of soil types approximately two thirds is thought to be mainly by denitrification (Addiscott and Powlson, 1992).

iii) Ammonia Volatilisation

The ammonium ion, being adsorbed to soil colloids by cation exchange on negatively charged sites, is not generally at risk of leaching from most soils. If, however, the soil pH rises, the equilibrium between NH_4^+ and NH_3 shifts towards the latter and evolution of NH_3 gas can occur (equation 2). This process is known as volatilisation.

$$NH_4^+ + OH^- \longrightarrow NH_3 + H_2O \qquad (2)$$

Rates of ammonia volatilisation are influenced by a number of environmental factors. Rachhpal-Singh and Nye (1988) consider among the most important of these are: aerodynamic factors affecting the transfer of ammonia from the soil surface to the atmosphere e.g. surface roughness, windspeed, temperature, pH and buffering capacity of the soil, soil moisture content, depth of application and the amount of urea applied. The effects of these factors on ammonia volatilisation losses can be explained on the basis of how each affects the equilibrium in equation 2.

Increased windspeed should lead to increased volatilisation by carrying ammonia away from the volatilising surface, shifting the equilibrium to the right. This effect has been reported in a number of laboratory studies and field studies of flooded soil surfaces, however, in field studies involving non flooded surfaces no relationship between windspeed and ammonia volatilisation has been found (Haynes and Sherlock, 1986). In the latter case, volatilisation from the soil surface was diffusion controlled, windspeed having little effect on the diffusion process at soil microsites. As with volatilisation from flooded surfaces windspeed by promoting mixing of air within the canopy, could be expected to increase ammonia volatilisation from urea deposited on the foliage.

Dissociation of NH_4^+ to NH_3, and in the case of urea hydrolysis urea to NH_4^+ (urease activity), increases with increasing temperature. The partial pressure of ammonia also increases with temperature. A marked effect of temperature on both the instantaneous rate and ultimate extent of ammonia volatilisation, and marked diurnal cycles in the rate of ammonia emission, mirroring temperature cycles, have been reported by a number of workers (Haynes and Sherlock, 1986).

Increasing pH increases OH^- concentration thereby pushing the equilibrium to the right, favouring ammonia volatilisation. Drying removes water from the right hand side of the equilibrium, thereby increasing ammonia formation (Adams and Martin, 1984). However, because urea hydrolysis requires water and proceeds very slowly in dry conditions (Volk, 1966), rapid volatilisation from urea only occurs when the soil surface is moist (Ferguson and Kissel, 1986; Mahli and Nyborg, 1979). Moisture from dewfall can be sufficient to significantly stimulate ammonia volatilisation (Hargrove *et al.*, 1977) and even humid air over dry soil can stimulate volatilisation (Reynolds and Wolf, 1987). Light rainfall usually stimulates volatilisation by moistening the soil surface and promoting urease activity (Black *et al.*, 1987; Craig and Wollum, 1982), while heavy rainfall or irrigation usually stops ammonia volatilisation by washing the urea into the soil (Craig and Wollum, 1982). Even light rainfall can dramatically reduce volatilisation if the soil is already at field capacity (Black *et al.*, 1987). While wind can increase volatilisation losses from moist soil surfaces, it can ultimately reduce total volatilisation by drying the soil surface (Ferguson and Kissel, 1986).

Ammonia volatilisation represents a major loss of nitrogen from agricultural systems involving animals (Jarvis and Pain, 1990). Ammonia can also be evolved from the foliage of arable crops. Normally these losses are likely to be less than 10 kg N/ha (Powlson, 1993), though Schjorning *et al.* (1989) have attributed losses of up to 40 kg N/ha from plants to ammonia volatilisation and Goulding *et al.*(1993) found evidence that losses up to 24 kg N/ha can occur in crops that are heavily over fertilised with nitrogen or are badly damaged by disease.

Nitrogen losses by volatilisation can be a problem for urea fertilisers applied to the surface of particular soils under certain conditions, for example dry calcareous soils (Ryden, 1984; Fenn and Hossner, 1985). Scharf and Alley (1988) reviewing a number of experiments, cite average maximum and mean volatilisation losses of 30 and 22% of N for urea applications to the soil. Further, they note that while there appears to be no difference between granular, prilled and solution urea as regards susceptibility to volatilisation, there are indications from the literature that losses are higher from broadcast applications of solutions than from dribble or stream applied solutions. Volatilisation losses of between 4 and 36% of N applied have been reported for foliar applied urea (Bowman *et al.*, 1987; Bowman and Paul, 1990b; Smith *et al.*, 1991) (Section 2.2.3 (iii)).

2.2.3 Nitrate Leaching

N as nitrate dissolves in water percolating through the soil and is washed out as the water drains. Mineral N occurring as ammonium, being subject to immobilisation, conversion to nitrate or held on cation exchange sites, is less likely to leach. With the exception of sandy soils with very low clay content, it is rarely leached from non acid soils in any quantity.

The amount of nitrate that is lost by leaching depends on the amount of water passing through the soil and the amount of nitrate in the soil when the water drains through and out of the profile. Thus drainage volume and amount of nitrate are the primary factors affecting nitrate leaching.

i) Factors Affecting Nitrate Leaching

a) Drainage Volume

The volume of water draining from a soil is primarily dependant on the soil type, the balance between rainfall and evapotranspiration and can be affected by cultivation methods.

Soil Type

Before drainage can occur and nitrate lost, a soil must reach and exceed its maximum water holding capacity. The volumetric moisture content of the soil is the main factor affecting capacity and varies according to soil texture (Addiscott *et al.*, 1991). Clay soils have a high volumetric water content and will reach maximum capacity later than sandy soils with a lower volumetric water content. Consequently, soil type affects the point at which drainage and thus potential nitrate leaching starts.

After the water holding capacity of the soil, the drainage volume depends on the rate at which water percolates through the soil. A main rate factor is the soil's hydraulic conductivity, which is also dependent on soil texture and structure (Addiscott *et al.*, 1991). Sandy soils, having a higher hydraulic conductivity, have higher percolation rates than clay soils. Nitrate in these soils is therefore at greater risk of leaching.

Rainfall and Evapotranspiration

The rate of percolation is also directly proportional to the water available for drainage (Bock, 1984). Once the soil has become saturated, this depends on the balance between precipitation (and/or irrigation) and evapotranspiration, drainage occurring when the amount of precipitation exceeds evapotranspiration (Goulding and Poulton, 1992). It follows that in the UK, drainage and therefore nitrate leaching, generally takes place during autumn, winter and early spring (Figure 2.4). Occasionally, it can occur in late spring and sometimes even in summer (Prins *et al.*, 1988).

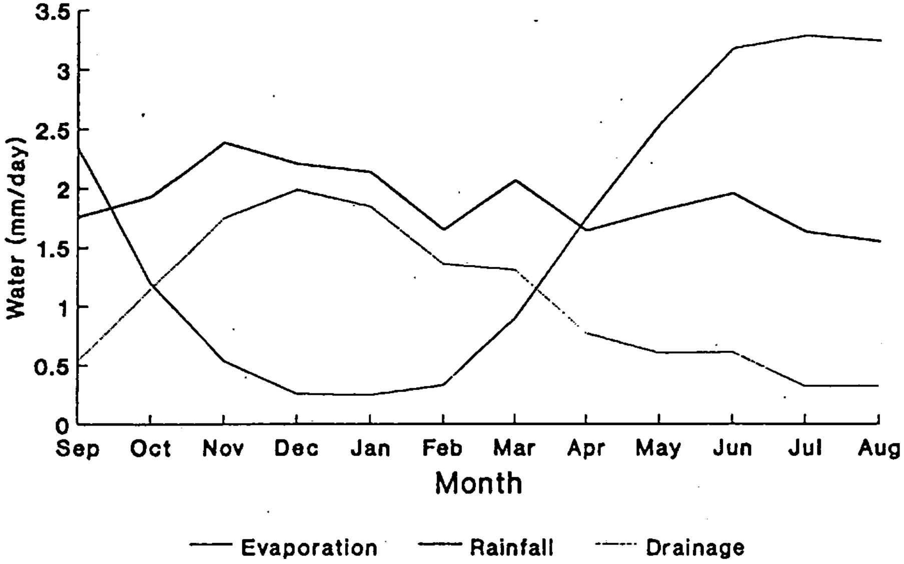


Figure 2.4 Monthly variation in average rainfall, evaporation and drainage through 0.5 m soil (after Addiscott *et al.*, 1991)

Cultivations

Simplified tillage (shallow tine cultivations or direct drilling) has been shown to reduce nitrate leaching losses in the autumn and winter, when mineralisation is the main source of nitrate, compared to ploughing (Goss *et al.*,1988; Goss *et al.*, 1993). The difference has been attributed to the greater continuity of vertically orientated macropores under simplified tillage than under ploughing (Goss *et al.*, 1984). This results in higher flow rates for direct drilled land, the macropores being rapidly purged of nitrates but leaching then depending on diffusion of nitrates from finer pores. In ploughed soil, the discontinuity reduces flow in the macropores, but allows more nitrate to diffuse from the finer pores, overall resulting in increased leaching (Goss *et al.*, 1988).

In the spring, however, the greater continuity of vertically orientated macropores results in greater leaching of fertiliser N from direct drilled plots, because the nitrogen is close to the soil surface and easily transported in rainwater to macropores and then downwards (Goss *et al.*, 1988).

b) Amount of Nitrate Present

The amount of nitrate present is affected by the amount of fertiliser N applied and the time of application, the extent of mineralisation/ immobilisation, and crop uptake.

Contribution of Fertiliser N

The two periods of the year likely to be associated with nitrate loss, notably winter and spring have already been outlined. The fate of fertiliser N in terms of recovery in the crop, in the soil or lost, is reviewed in Section 2.2.4.

Considering the contribution of fertiliser N to leaching losses in the spring just after application, work at Rothamsted (Section 2.2.4 (iii)) using ^{15}N labelled fertiliser applied in the spring to autumn sown crops has shown that the percentage of fertiliser N unaccounted for in the crop or soil at harvest and therefore presumed lost between application and harvest, ranges from 4-

38 percent. Considering this data, covering a range of soil types and sites, Powlson *et al.* (1992) found a linear relationship between loss of fertiliser N and rainfall in the three week period following application, each additional 10 mm of rainfall increased the loss by 2.6 percent. Rainfall, however, could favour loss by increasing leaching or denitrification or both. Addiscott and Powlson (1992), have further partitioned the estimated losses between these two processes using the model of Addiscott and Whitmore (1987) to simulate leaching, mineralisation of organic N and mineral N uptake by the crop. In only two out of thirteen experiments was the loss totally attributed to leaching, and in one of these the loss was very small. In one of the experiments the loss was totally attributed to denitrification. In the remaining ten experiments, both pathways were implicated, however, nearly two thirds of the total loss was attributed to denitrification and one third to leaching. This represented on average, 5% of the fertiliser N lost due to leaching between application and harvest. This together with direct measurements (Goss *et al.*, 1988) indicates that fertiliser N is not a major source of nitrate leaching in spring.

This applies to the climatic conditions of Southern and Eastern England. In the wetter areas of the UK, where the main leaching period extends into late spring, the situation could be different. It is further notable, that these findings were based on losses of spring fertiliser N applied to autumn crops that were already well established and actively taking up N at the time of application. N applied to spring cereals is likely to remain in the soil for several weeks before uptake begins and is consequently at greater risk of leaching than that from equivalent applications to winter cereals.

With respect to nitrate leaching losses in the autumn and overwinter, fertiliser N remaining in the soil after harvest ranged from 13-36% (mean 20%) where labelled N was applied as $^{15}NH_4$ and less (7-14%) where N was applied as $K^{15}NO_3$ (Section 2.2.4 (iii)). MacDonald *et al.* (1989) has partitioned the residual fertiliser N between inorganic and organic N and found 80-90% of the residual fertiliser N was in organic forms. In most cases only 1-2% of the fertiliser N remained as inorganic N after harvest and could therefore potentially contribute directly to leaching.

The direct contribution of fertiliser N to nitrate leaching can therefore be no more than about 6-7% (Addiscott *et al.*, 1991). This estimate is supported by direct measurements. Dowdell *et al.* (1984b) recorded 6.3-6.6% of the labelled fertiliser N applied to spring barley in the drainage water from lysimeters over four years following its application. Goss *et al.* (1988) recorded nitrate leaching losses of approximately 6-7% of the spring fertiliser applied before cessation of drainage in the spring; and Vinten *et al.* (1991) have reported similar results.

The proportion of fertiliser N recovered in the soil at harvest (Section 2.2.4 (iii)) is remarkably constant, given the range of soil types, crop and weather conditions. This is due, in part at least, to the range of N rates used, normally only up to the optimum. Fertiliser rate, however, can affect the amount of nitrate present in the soil and therefore potentially at risk to leaching during autumn and winter. The relationship is not a simple linear one; a "breakthrough effect" occurs when N applied exceeds the economic optimum. Glendening *et al.* (1992) studying the Broadbalk wheat experiment, found that the soil nitrate content measured at harvest or later, was approximately constant for N applications up to that which gave maximum yield response, but at rates above this increased sharply. Chaney (1990) reported a similar pattern, although in contrast to the results from the Broadbalk experiment, the increase did not occur until well after the yield (and economic) optimum were reached. Lord (1992) reviewed published and unpublished data and derived average gradients for relationships between leachable nitrate and fertiliser N applied. She reported an increase in leached N for cereals of 7 kg/100 kg of fertiliser N applied up to a "break point", above which the response increased to 50 kg/100 kg of fertiliser N. The breakpoint occurred close to the economic optimum. Vinten *et al.* (1991) measuring nitrate leached, also found little effect of fertiliser N applied up to the recommended rate. A similar break through effect has been reported by Barraclough *et al.* (1992) for grassland.

Recently Davies and Sylvester-Bradley (1995) have contested the contribution of fertiliser N to nitrate leaching as reviewed here. Citing research by a number of workers (Chaney, 1990; Sylvester-Bradley and Chambers, 1992; and Lord, 1992), they observe that "there is on average a small but measurable increase in mineral N of about 7 kg / 100 kg of fertiliser N applied <u>below the optimum</u>". While this is correct, it cannot be considered a <u>direct</u> effect of fertiliser N, in terms of fertiliser N remaining in the soil at harvest, as reported by MacDonald *et al.* (1989) and as discussed by Addiscott *et al.* (1991).

In reviewing the contribution of fertiliser N to nitrate leaching, the discussion has centred on spring applied fertiliser N. Timing of application of fertiliser N, however, will affect this. Crop recovery of fertiliser N is improved when application coincides with high uptake. Autumn applied N is used less efficiently by winter cereals than spring applied N (Sylvester-Bradley *et al.*, 1987; Powlson *et al.*, 1986b) and is therefore much more likely to leach. It is now normal agronomic practice to delay N applications to winter cereals until the spring (Chalmers *et al.*, 1990; MAFF, 1994b).

Mineralisation

Leaching losses of nitrate directly attributable to fertiliser N in the order of 6-7 percent of that applied, correspond to a loss of 13 kg N/ha for an average 190 kg N/ha application (Chalmers *et al.*, 1990). Measurements show that far more than this is leached in practice depending on soil type, drainage and management (part (ii) this section). This difference is now considered to be attributable to organic N mineralised in the autumn. This nitrate is vulnerable to leaching; the soils are wetting up and drainage is starting and there is little if any actively growing crop to catch it.

This naturally occurring nitrate is now considered to be the biggest cause of the nitrate problem, responsible for a larger proportion of nitrate losses than nitrogen fertilisers (Addiscott *et al.*, 1991). This conclusion is supported by the analysis by Addiscott (1988) of the Rothamsted drain gauge data for the period 1877/8-1914/15. The calculated quantity of N leached as nitrate derived from soil N over the 38 years was 1444 kg/ha, which agrees closely with the corresponding measured decline in soil nitrogen. Given that the soil in the gauges carried no crop and received no fertiliser and that the mineral N in the soil is a small fraction of total N, practically all losses must have been derived from soil organic nitrogen.

Factors affecting mineralisation will thus affect nitrate leaching. The effect of soil type and weather with respect to mineralisation have already been noted and are obviously beyond the farmer's control.

Cultivation, by improving soil aeration, also promotes mineralisation and therefore increases the amount of nitrate at risk to leaching. This effect had long been appreciated when permanent pasture was ploughed up. Davies *et al.* (1979) found evidence of the effect, though to a significantly lesser extent, in long term arable soils. More recent reports; Shepherd and Lord (1990) and Goss *et al.* (1993) support this.

Goss (1990) has reported a decrease of 10 kg N/ha in N leaching losses from direct drilled plots compared to tilled plots and attributed this to reduced mineralisation. The contribution that higher drainage flow rates in uncultivated or minimally cultivated land, as discussed earlier, made to these differences, rather than the process of mineralisation itself, is not made clear. Occasionally, cultivation fails to promote mineralisation (Dowdell and Crees, 1980) but reasons for this are not clear. It may be that where the mineralisable N residues are low, soil disturbance has little effect.

The contribution that mineralisation following cultivation makes to nitrate leaching, depends on the timing of cultivation in relation to drilling of the next crop and to prevailing temperatures. Shepherd *et al.* (1992) found that delaying cultivation until just before drilling delays the onset of mineralisation and this reduces the risk of leaching, while Stokes *et al.* (1992) found that delaying cultivation reduces the extent of mineralisation itself. This effect, however, cannot be relied upon; Davies and Rochford (1992) obtained a benefit from delayed cultivation in terms of reduced nitrate leaching, in only one year of a two year experiment.

Immobilisation

The process of immobilisation has been outlined (Section 2.2.2); by this process potentially leachable N can be removed from risk. As a result of recent legislation, straw incorporation is now the norm in the UK. Immobilisation associated with the decomposition of cereal straw is well documented (Patterson, 1960; Short, 1973; Lord, 1988). A number of workers have shown this can contribute to reduced leaching in the short term (Powlson *et al.*,1985; Bertilsson, 1988; Jarvis *et al.*, 1989; Goss, 1990); however, more recent work on a chalk soil in Cambridge (Davies and Rochford, 1992) showed no consistent benefit from incorporation, suggesting that it cannot be relied on to reduce nitrate leaching. Further, in the long term, additional organic N due to immobilisation leads to an increase in the basal rate of soil mineralisation (Powlson *et al.*, 1987(b)). This may account for recent observations of a more linear relationship between fertiliser N rate and nitrate leaching in the Broadbalk experiment (Goulding and Webster, cited in Powlson, 1993).

Crop Uptake

Uptake of mineral N by the crop also removes potentially leachable nitrate from risk. The presence of an actively growing crop and factors affecting crop uptake will thus affect nitrate leaching.

The presence of a growing crop during the autumn and winter has been shown to reduce nitrate leaching compared to bare soil (Catt *et al.*, 1992). To be effective, however, an autumn crop must be sown early. Sowing earlier rather than later enables the development of a more extensive root system earlier, enabling more of the nitrate made available by mineralisation to be "tapped". Work by Widdowson *et al.* (1984 and 1987) has demonstrated the effect of early sowing on reduced nitrate leaching. Goss *et al.* (1993), however, has suggested that only very early sowings (mid September) or very late (late November) are likely to affect total winter leaching losses. Further, early sowing can conflict with aspects of good husbandry; weed control with minimal use of herbicides and carry over of pests and disease.

Crop vigour will affect leaching; a well established vigorously growing crop will utilise more nitrate than a backward crop.

In the case of spring crops, a winter cover crop ploughed under in the spring can take up nitrate from the soil during autumn and winter and reduce nitrate leaching in the short term. A number of workers have shown the importance of cover crops in this respect; Nielson and Jenson (1985), Christian *et al.* (1992), Shepherd and Lord (1990), Davies and Rochford (1992), and Johnson *et al.* (1992). Fielder and Peel (1992) have noted the importance of early establishment of the cover crop with respect to the potential to reduce nitrate leaching.

The use of cover crops to reduce nitrate leaching in the short term, however, may have implications for nitrate leaching in the longer term. Some of the N released following incorporation of the cover crop will not be well synchronised with N uptake by the subsequent crop and may be subject to leaching; Catt *et al.* (1992) have reported evidence of this in the Brimstone Experiment. Further, the effect of increased organic N in increasing the basal rate of soil mineralisation in the longer term (Powlson et al., 1987b) has already been noted. Powlson (1993) has noted the importance of a clearer understanding of the time-course of N released following incorporation of cover crops in this respect.

ii) Estimates of Nitrate Leaching

The large number of climatic, soil and husbandry factors that influence nitrate leaching make general estimates of nitrate leaching impossible and direct comparisons of research findings difficult.

Kolenbrander (1981), considered the results from a number of experiments and adjusted them to equate to an annual drainage of 300 mm. On the basis of this data he predicted mean annual leaching losses of 100 kg N/ha and 42 kg N/ha for sandy and clay soils respectively growing arable crops and receiving 170 kg/ha of fertiliser N.

Dowdell *et al.* (1984b) applied 80-120 kg N/ha to spring barley grown on chalk soils in lysimeters and recorded mean annual leaching losses over four years of between 65-83 kg N/ha corresponding to mean annual drainage of 340-460 mm. Differences between fertiliser treatments were not significant. In another lysimeter study, Webster *et al.* (1986) recorded leaching losses under an arable rotation of 34-129 kg N/ha, corresponding to 259-427 mm drainage from sandy soils and 15-73 kg N/ha corresponding to 174-420 mm drainage from clay soils.

Davies and Archer (1990) note a general figure of 20 kg N/ha for estimated leaching losses in "average field situations", but do not specify any soil type. Goulding and Poulton (1992) cite a similar figure for sandy soils and 10 kg N/ha/year for clay soils based on a range of experiments. Lord (1992) from a range of published and unpublished data has estimated average nitrate leaching from winter cereals in the UK to be in the order of 35 kg N/ha/year at optimum amounts of fertiliser N applied.

To put these figures in perspective, assuming no denitrification occurs below the agricultural soil level, by simple calculation, the EC limit of 11.3 mg/l nitrate-N in potable and surface waters is equivalent to an average annual leaching loss of nitrate-N, directly related to drainage as shown in Table 2.2.

Table 2.2 Effect of excess winter rainfall on the average quantity of nitrogen loss per hectare which equates to 50 mg/l in soil water (after Archer, 1992).

Drainage (mm)	Nitrate-N leached (kg/ha/yr)
150	17
250	28
350	40

Leaching losses in the order of 20 kg N/ha in the drier parts of Eastern England with annual drainage of less than 150 mm, therefore suggest that leachate concentrations are usually in excess of the EC limit.

iii) Measuring Nitrate Leaching

A number of methods are available:

a) Lysimeters

Early lysimeters of the repacked type, due to the disruption to the natural flow of water (Joffe, 1932), proved to be of little value and are not used today.

Lysimeters used today, consist of undisturbed soil and can be classified as two types: Ebermyer lysimeters are constructed by digging a trench alongside the block of soil of interest, excavating horizontally beneath it and inserting a collection vessel (Barbee and Brown, 1986). With respect to relevance to the field situation and interpretability of the data, Addiscott (1990) in a review of the methods noted the main problem of this type of lysimeter is the lack of any lateral constraint to water movement; they have no side walls. There is no way of knowing exactly what area the water and nitrate collected is derived from. No studies have been reported on the reproducibility of data from this type of lysimeter, though the main factor would probably be soil variability.

Monolith lysimeters consist of large undisturbed blocks of soil cut from the ground and encased so that all water and nitrate draining from them can be collected via some system at the base (Belford, 1979). The lysimeter may be reinstalled at the site or moved elsewhere. Problems include the technical difficulties associated with moving up to 1.5 tonnes of soil *en bloc*, vertical and lateral compression of soil next to the container walls and the structural collapse of unstable soils on collection. The full cost of removal and installation is around £2000 per lysimeter (Goulding and Webster, 1992). With respect to relevance Addiscott (1990) noted the lateral constraint imposed by the side walls of the containing vessel means that while water and nitrate are collected from a known area, by definition, lateral flow is prevented. This is likely to be of less relevance in sandy soils than clay soils. With respect to reproducibility, as with Ebermyer lysimeters, this is likely to depend largely on the variability of the soil. Problems can arise on clay soils, however, in dry weather when shrinkage of the soil away from the side walls allows by-pass of the soil block.

With both types of lysimeter, the surface tension of soil water where it is in contact with air at the base interrupts the tension that would naturally be applied to soil water as a result of water in deeper layers and reduces drainage compared to soil in its natural state (Coleman, 1946). In addition to affecting flow rate, tension at the lysimeter base also affects which pores drain. This can influence both the flux and concentration of nitrate at the soil base (Haines *et al.*, 1982). They concluded that saturated flow was sampled more efficiently without tension and that unsaturated flow sampled more efficiently with tension. The application of tension to the base of the lysimeter is therefore important, how much tension should be applied depends on the tension at depth in the natural state and no generalisation can be made.

b) Large scale Field Drainage Collection

Taking advantage of the natural impermeability of heavy clay soils to downward water movement enables drainage water and nitrate to be collected on a large scale. Except when they dry out and crack, water and solutes in clay soils move in three main flow systems: surface run off, lateral flow at the surface of the sub soil (interflow) and flow in mole drains in the subsoil. Hydrologically isolated plots can be created in which water and nitrate flowing in each of these flow systems is collected. Leaching can thus be measured directly in the true field situation, the Brimstone Experiment is an example (Catt, 1991).

In Addiscott's (1990) review of methods of measuring nitrate leaching, workers considered large scale field drainage collection, as a method of measuring nitrate leaching, very relevant. The soil is largely as it would be in the field, lateral flow is not a problem as it is collected and any air-water interfaces are as they would be in the field. Interpretability of the data is also high, the drained area being clearly defined and concentration and fluxes of nitrate in all three flows can be calculated. The main drawback of such large scale experiments is cost, Goulding and Webster (1992) estimated that the Brimstone Experiment would now cost some £250,000 to construct.

c) Soil Sampling

The simplest method of estimating *potentially* leachable nitrate is to take 5-10 soil samples to around 90 cm divided into different depths, bulk the soil from each depth and extract and determine the amount of nitrate (and ammonium) at each depth. This method gives the mineral N profile of the soil and how much nitrate (and ammonium which could be nitrified) is *at risk* to leaching.

Differences between successive samplings provide an estimate of the change in the amount of nitrate in the profile. However, such changes cannot necessarily be attributed to leaching, other processes cause nitrate to disappear (crop uptake, immobilisation and denitrification), and mineralisation of organic N adds fresh nitrate. Soil sampling data also tends to be highly variable. Lord and Shepherd (1993) noted c.v.'s in the order of 30 - 40% for 10 bulked cores per point sample on arable soils and up to 130% for single cores. The method has the further disadvantage of poorer sensitivity for nitrate than direct solution sampling at the same detection limits. Due to dilution during the extraction process, the limit for detection of nitrate may be no better than 10 mg/l N, i.e. the EC limit (Goulding and Webster, 1992). Given these drawbacks, compared to other methods soil sampling was considered of low relevance with respect to estimating nitrate leaching in the field and difficult to interpret by a number of workers (Addiscott, 1990).

Computer simulation of the alternative pathways and sources of nitrate, together with an estimate of drainage and knowing the moisture content of the soil allows an estimate of leaching to be made (Powlson *et al.*, 1989b). The problem appears to be finding a model that works satisfactorily.

d) Porous Ceramic Suction Cups

Sampling of soil solution by this method is well established (Briggs and McCall, 1904). The typical construction of cups in use today, and as used in this study, has been described by Webster *et al.* (1993) (Figure 2.5). The cups are installed vertically, horizontally or at an angle into an augured hole. A slurry of silica flour is usually poured into the hole to ensure good cup to soil contact and the hole back filled with soil in the correct order.

Vertical installation is the simplest, but also carries the greatest risk of preferential flow to the cup due to disturbed soil and sampling tubes immediately above the cup. Water passing through the soil may also have different nitrate concentrations to that passing through consolidated soil. A bentonite plug is thus commonly inserted around the sample tubes 5-10 cm below the plough layer to divert water flowing down the installation hole to undisturbed soil. Vertical installation is also likely to suffer the greatest risk of any crop damage incurred in sampling visits affecting nitrate concentrations. Lord and Shepherd (1993) found no significant difference between angled and vertically installed cups, but noted that angled installation would be a sensible precaution, particularly in short term studies where soil disturbance will have greatest influence.

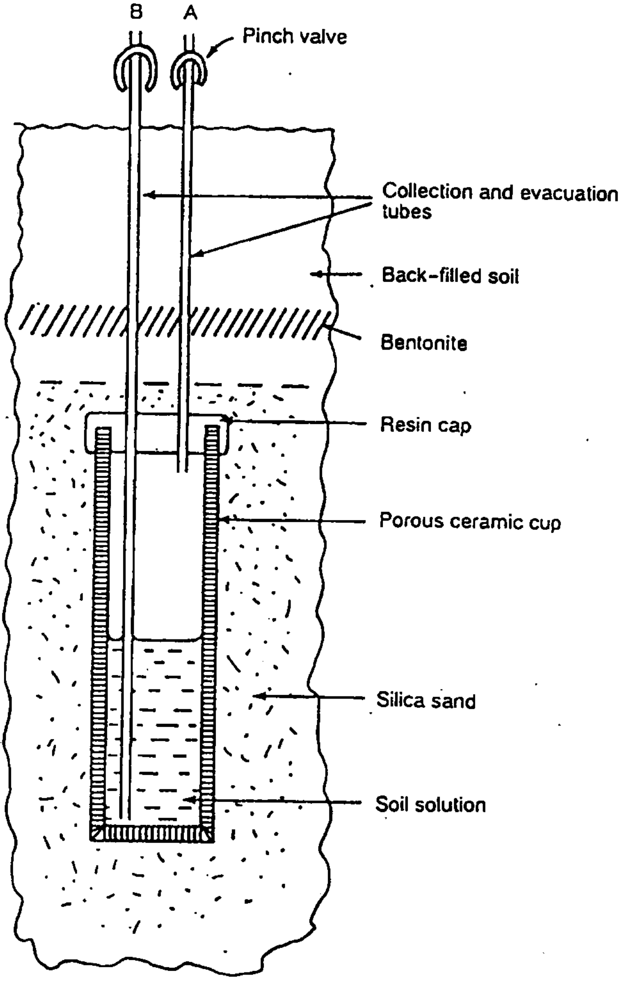


Figure 2.5 Ceramic suction cup used to collect samples of soil water (after Webster *et al.*, 1993)

Samples are obtained by applying a vacuum to the cup of up to 80 kPa for 10-120 minutes using a small hand pump or a gas syringe and then collecting the sample, again by suction.

The advantages of porous cups over other methods are that they are relatively cheap (around £20 per cup) and easy to install, there is minimal soil disturbance during subsequent sampling and they are simple to use (Grossman and Udluft, 1991). A number of problems, however, have been noted:

Ceramic cup results tend to be highly variable. Hansen and Harris (1975) concluded that variabilities of +/- 30% or more are to be expected in the field, when measuring concentrations in the order of 20 mg/l. Lord and Shepherd (1993) have reported c.v.'s of 30-70%, depending on crop type, though variability for cereals tends to be lower than for other crops (35-55%). Variability is far worse under grazed grassland where there are faeces and urine patches (Cuttle, 1992). Variability is probably due in part to the intrinsic variability of the cups themselves, in part to the slight differences in installation and the remainder to soil variability (Addiscott, 1990). Variability, however, is still less than for soil samples (Lord and Shepherd, 1993).

In terms of interpretability and relevance of the data, a number of questions have been raised. England (1974) noted that; "one cannot be sure from what macroscopic volume of soil the sample was extracted nor from which pores". With respect to "what volume", Van der Ploeg and Beese (1977) concluded from calculations that porous cups could sample water from a sphere of approximately 0.6 m diameter, including mobile and non mobile water. They also suggested that applied over a long period, sampling suction could also distort the natural drainage pattern. These calculations, however, are more relevant to continuous sampling systems extracting large sample volumes. Lord and Shepherd (1993) conclude that discrete sampling every 14 days removing small sample volumes (15-20 ml) should not affect the natural drainage pattern. Discrete sampling, however, introduces the risk that important changes in the nitrate concentration of the drainage water may be missed. Goss *et al.* (1988) have shown the changes in nitrate concentration that take place during a single storm event (Figure 2.6). A single sample, such as that taken by a porous cup, will have a very different nitrate concentration depending on when during the drainage event it is taken. It may therefore be expected to lead to an under or overestimate of nitrate leaching. This, however, as will be seen, is not found in practice for sandy soils. Further, Lord and Shepherd (1993) from an analysis of three data sets found that omitting subsets of samples (four strategic combinations of subsets tested) had little effect on the calculated loss. Even using only four samples (of eleven), calculated losses were within 10% of that calculated from the full data set.

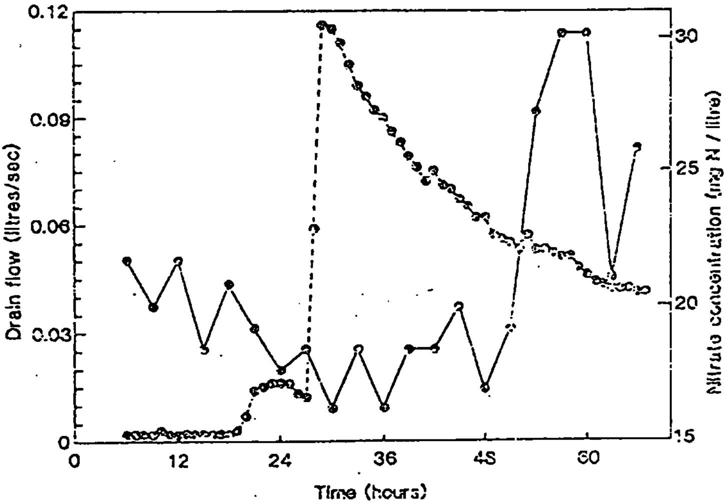


Figure 2.6 Drainflow (---) and concentrations of nitrate (—) in the drainage water during one storm event at Brimstone Farm (after Goss *et al.*, 1988)

With respect to "which pores", the existence of mobile and immobile water becomes a problem in terms of the relevance of porous cup data in determining fluxes of nitrate, since such fluxes involve mobile water. Porous cups are most useful in sands and in other soils in which water flows through a reasonably large proportion of the soil pores and also in types of chalk in which matrix flow occurs. They are less useful in those soils with water in clearly defined mobile and immobile phases, such as silts and clays.

A number of workers have shown this. Barbee and Brown (1986) applied chloride to three different fallow soils and allowed it to leach naturally and compared the chloride concentrations in the soil water as detected by porous cups and an Ebermyer lysimeter. There was no significant difference in chloride concentration or time of peak concentration between the two sampling systems on the sandy soil. On the silt loam, however, there was a significant difference in the pattern of leaching, peak concentration in the cups was higher and occurred earlier than that detected by lysimeter. In the clay soil the porous cup produced enough sample for analysis on only one occasion and was by-passed on others. This comparison could be criticised on the basis that no suction was applied to the lysimeters used; however, Shafer *et al.* (1979) also found evidence that porous cups could be by-passed by percolating water in a clay silt loam. In one experiment, compared to samples collected from lysimeters, porous cups failed to detect a large concentration of nitrate moving downwards and in another failed to detect a large nitrate concentration and a "spike" of cadmium. Cadmium being strongly adsorbed, does not leach in normal circumstances and bypass flow through larger pores was therefore indicated. Such flow would have been encouraged by the large volume (16.6 mm aliquots) of solutions applied. Unlike the experiment of Barbee and Brown (1986) this study used lysimeters with and without suction. Further evidence that ceramic cups are by-passed by mobile water has recently been provided by Goulding and Webster (1992). They have compared soil water nitrate concentrations in cups in the moderately structured silty clay loam of the Broadbalk field with that flowing from drains before and after N applications. Much higher N concentrations were recorded in the cups than in the drains before N application, while the reverse was true after N application; a good indication that the cups sample immobile water and the drains mobile water.

Webster *et al.* (1992 & 1993) compared porous cups and monolith lysimeters as a method of estimating nitrate concentration in drainage water and nitrate leaching losses at two sites over three years. Profiles of nitrate concentration with cumulative drainage were similar, but peak concentration while of similar magnitude occurred earlier for porous cups than for lysimeters. This was supported by bromide concentrations measured in a separate bromide tracer experiment. The effect was attributed to faster anion flow in the plots with cups compared to lysimeters, due to the absence of matric suction pressure applied at the lysimeter base (only partially applied). With respect to nitrate leached, apart from the first year, when significant differences between porous cups and lysimeters were attributed to soil disturbance, good agreement was found between the two methods at both sites. They concluded that porous cups are an acceptable method of measuring nitrate leaching losses on free draining soils if used correctly. Other workers have reported apparently satisfactory results on a range of light and medium soils (Davies and Rochford, 1992; Shepherd *et al.*, 1992).

From the literature then, porous cups are a relatively cheap and simple method of measuring nitrate concentrations in sandy and other relatively unstructured soils. The data is less variable than soil core data and can be analyzed with greater precision. It is notable, however, that in Addiscott's review of methods (1990), soil coring, with respect to "scientific attributes" (reproducibility, relevance, mobile/immobile water and interpretability), received no lower scores than porous cups.

Porous cups, however, due to the unknown volume drained, do not measure nitrate leaching directly. To do this necessitates an estimate of drainage volume. This is usually obtained from weather based models of rainfall and evapotranspiration such as MORECS (Thompson *et al.*, 1981) or Irriguide (Spackman, 1990).

Webster *et al.* (1992 & 1993) found good agreement between over winter drainage as calculated by these meteorological methods and that recorded by lysimetry. This agreement, however, hides the fact that the pattern of drainage in the lysimeters was not the same as that which occurred naturally in the field. Although the lysimeters were equipped to allow free and suction assisted drainage, it was only applied for a few hours per week. In the field matric suction pressure would have always been present. Further, the single estimate of drainage flux as calculated by either system, is then applied to all sample points i.e. drainage is assumed to be uniform. In practice, due to the spatial variability of the soil, this will not be the case (Addiscott, 1990). When estimating drainage by meteorological methods, Lord and Shepherd (1993) have noted the importance of accurate determination of the start of drainage and of the failure to sample the first flow.

In terms of a "best buy", porous cups at the base of the rooting zone offer a reasonable economic method, on light to medium textured homogenous soils, of measuring nitrate concentrations in soil water. In conjunction with meteorological systems to determine drainage, an estimate of nitrate leaching can be made. On balance, lysimeters offer a more reliable guide to nitrate concentrations and nitrate leaching over a wider range of soils, but at significantly higher cost. On heavy clay soils large scale drainage collection systems are the only reliable option.

iv) Strategies to Reduce Nitrate Leaching

Methods to reduce nitrate leaching can be considered as agronomic or governmental.

a) Agronomic Measures

On the basis of the factors affecting nitrate leaching (Section 2.2.3 (i)) a set of guidelines have been produced and are embodied in the Code of Good Agricultural Practice for the Protection of Water (MAFF, 1991). The code has statutory support under the Water Act (Anon., 1989) and is a requirement of the EC Nitrate Directive (Council of European Communities, 1991). The agronomic measures with respect to arable crops can be summarised as:

1. Nitrogen fertiliser should not be applied in the autumn.

2. Nitrogen applications should be optimised with regard to anticipated yield and applied in relation to crop demand and in accordance with professional recommendations.

3. Where possible applications of nitrogen should be split to reduce the risk of nitrate leaching.

4. Application equipment should be regularly calibrated and fertiliser spread accurately avoiding ditches and hedges.

5. Wherever possible soils should not be left bare over winter. In the case of spring sown crops catch crops should be sown overwinter.

6. Winter sown crops should be sown early in the autumn.

7. Straw should be incorporated where possible.

8. Cultivations should be delayed until just prior to sowing to delay the build up of nitrate in the soil.

9. Ploughing in of temporary grassland or permanent pasture should be managed carefully and avoided if at all possible.

10. Applications of organic manures should be related to crop requirements and limited to no more than 250 kg N/ha in organic manure in any 12 month period. Applications to arable land in the autumn and early winter should be avoided.

11. Irrigation should be carefully scheduled to avoid returning the soil to field capacity during the growing season.

Those guidelines that increase farm efficiency, such as optimum use and timing of fertiliser, are likely to require little more than better education. However, those that entail or are perceived to entail a degree of risk, expense or inconvenience, e.g. earlier sowing date, may require enforcement of the code of practice. While it is supported by legislation, how effective this will be remains to be seen.

Early results from a study by Johnson (1992), from two rotational trials in which the above guidelines were compared to "standard husbandry practice" have indicated that nitrate loss can be reduced with only a small reduction in farm income. This study was very short term and questions as to whether the economics of the systems change with time and whether the reduction in nitrate loss results in increased losses in later years need to be addressed.

It is generally recognised that implementation of good farming practice alone will not reduce nitrate leaching to within EC limits (Foster *et al.*, 1986). Williams (1990) has suggested that implementation of such agronomic measures is likely to reduce nitrate leaching by only about 10%, but up to 25% in certain crops.

b) Governmental Measures

Taxes

Taxation, at a rate of 49%, has been imposed on fertilisers in Sweden, Finland and Austria, but has had limited effect on nitrogen use. A model by Williams (1990) has suggested that a tax of 40% in the UK would have little effect. The lack of impact is a direct reflection of the effect of nitrogen on crop yield. The principle effect of N taxation would be to redistribute income from farms to the exchequer. Williams (1990) predicted a decrease in national net farm surplus of £130M (16%) with a tax of 40%.

Quotas

Production quotas have been used to curb over production in a number of sectors. Quotas on inputs have been suggested to curb over production and at the same time control environmental pollution.

The model of Williams (1990) indicates that N quotas would be more effective than N taxation in reducing nitrate leaching . Sylvester-Bradley *et al.* (1987) have reported that 90% of cereal yield can be obtained using only 40-50% of optimum N input. Quotas would therefore also be less of a financial burden to farmers. According to Williams (1990) reducing fertiliser applications to 80% of their current levels would reduce net farm surplus by £70M (9%).

While quotas may appear promising, problems can be anticipated as a result of farmers likely responses to them in an attempt to maintain margins. Nitrogen fixing break crops would be likely to be introduced and nitrogen devoted to higher margin crops which, coincidentally, tend to leach larger amounts of N, e.g. potatoes.

The predicted effects on net farm surplus on a national scale of taxes and quotas also masks differential effects according to size and type of farm.

Restrictions On Land Use

Comprehensive restrictions on land use

This is the only agricultural solution which by itself would approach the requirement of the EC Nitrate Directive, and Williams (1990) estimates that up to 80% of arable land in those areas where the nitrate limit is exceeded would need to be converted to unfertilised grass or woodland. The financial implications would be considerable, with a reduction of some 50% in national net farm surplus. The implications for the agricultural industry as a whole and rural communities would be massive and probably publicly unacceptable.

Local restrictions on land use

In 1990 the UK government introduced the Pilot Nitrate Scheme. Ten nitrate sensitive areas (NSA's) were designated, over a range of sandstone, chalk and limestone groundwater sources with high and/or rising nitrate levels. Under the scheme compensation is paid to farmers who voluntarily agree to reduced inputs and altered management practices to reduce nitrate leaching. The scheme consists of two parts:

(1) Under the basic option the same farming system continues as before, but farmers were required to observe prescribed limits on inorganic and organic fertiliser amounts and timings, and to establish a cover crop on land left bare in the autumn.

(2) Under the premium option, farmers were required to convert arable land to permanent grassland. A number of management options exist:

- unfertilised, ungrazed grass.
- unfertilised, grazed grass.

- limited fertiliser and optional grazing.
- grassland with woodland.

The Pilot Scheme closed for entry in May 1991. Agreements are set to run to 1995 or 1996, according to when the farmers joined. Farmer uptake of the scheme has been high, 87% of the land and 80% of the farmers have joined.

A "New" Nitrate Scheme was launched in 1994 (MAFF, 1994c) as part of the governments measures designed to comply with the EC Agri-Environment Regulation (EC 2078/92). The scheme established a further 22 NSA's and incorporated the existing 10 NSA's from the pilot scheme. The scheme is scheduled to run for five years. The scheme is again voluntary and compensated for. Farmers are able to choose between three options:

(1) Basic option: Low nitrogen arable cropping. This requires application of inorganic fertiliser to be limited to 150 kg N/ha. No organic N will be permitted and cover crops will be required to be established on land left bare in the autumn. Potatoes and vegetable brassicas will be banned. Alternatively, a sub-option allows any crop to be grown, with fertiliser N applied according to crop requirements (up to 200 kg N/ha), in one out of the five growing seasons.

(2) Premium arable option: Conversion of arable to extensive grassland. A number of management options exist:

- unfertilised, ungrazed grass.
- unfertilised, ungrazed grass, with native grass species.

- unfertilised, limited grazing.
- limited fertiliser/grazing.

(3) Premium grass option: Conversion from intensive to extensive grass.

Compensation payments are between £65 and £590 per hectare according to which option is chosen.

In addition to the New Nitrate Scheme, under the EC Nitrate Directive (Council of European Communities, 1991), member states were required to establish and designate nitrate vulnerable zones (NVZ's). 68 NVZ's in England and Wales, totalling 600,000 ha and 1 in Scotland of 435 ha have recently been designated (MAFF, 1996a; Scottish Office, 1996). The new NSA scheme is seen as a voluntary supplement to the mandatory measures that will apply in the NVZ's.

Under the Nitrate Directive, member states are required to establish action programmes in respect of the designated vulnerable zones for the purpose of reducing and preventing fresh surface or groundwaters from reaching a concentration of 50 mg/l nitrate. The action programme proposed for NVZ's in England and Wales (MAFF, 1995b) incorporates the following measures:

Inorganic N fertilisers:

- should not be applied between 1 September and 1 February unless there is a specific crop requirement.
- should not be applied to water logged, flooded, frozen or snow covered soils, steeply

sloping fields, or in such a way that they may directly enter surface water.

- should not exceed crop requirements, taking account of N supply from soil organic matter, crop residues and organic manures.

Organic manures:

- applications should not exceed 250 kg N/ha on average for grass fields and 210 kg N/ha on average for fields not in grass. The latter is expected to be reduced to 170 kg N/ha by 2003.
- on sandy or shallow soils; slurry, poultry manure or liquid digested sludge should not be applied between 1 September and 1 November to grass fields and between 1 August and 1 November for fields not in grass.
- organic manures should not be applied to water logged, flooded, frozen or snow covered soils, steeply sloping fields, or in such a way that they may directly enter surface water.

Storage of slurry and silage:

- all new or substantially altered slurry or silage facilities must conform with the Control of Pollution (Silage, Slurry and Agricultural Fuel Oil) Regulations 1991.
- Storage capacity for organic matter which cannot be applied in the autumn must be adequate to cover the closed period, unless other environmentally acceptable means of disposal are available.

Fertiliser records:

- records of N fertiliser and organic manure use must be kept.

With certain exceptions, the proposals therefore largely reflect the Code of Good Agricultural Practice for the Protection of Water (MAFF, 1991). Unlike the code, however, the proposals will be mandatory and enforceable by law. The deadline for implementation of the action programmes is 1999.

No compensation will be paid to farmers in NVZ's in respect of any costs incurred in implementing the proposed action programme, however, grants will be made available to those farmers in the zones who have to improve their waste handling facilities as a result of the limits which the proposed action programme sets on manure spreading. The initial capital costs (one off) to the industry of implementing the measures are estimated at £10M, and the ongoing annual costs, including interest arising on capital invested, are estimated at £3M (MAFF, 1995b). In addition to these direct costs it has been suggested that NVZ's may reduce land values, particularly in the longer term, due to the perceived risk of future changes to the regulations (Cowap, 1996).

2.2.4 Recovery of Fertiliser Nitrogen in the Crop

i) <u>Methods of Measuring</u>

Recovery of applied nitrogen can be determined by four methods (Hauck and Bremner, 1976).

<u>Non Isotopic Methods</u>

(1) <u>Non isotopic difference method</u>

Recovery of fertiliser N by the crop is calculated from the difference between total nitrogen uptake from a fertilised plot and from a control plot given no nitrogen fertiliser. This method places considerable weight on the performance of the control plots, which may be very nitrogen deficient. Further, inherent in this method is the assumption that immobilisation/mineralisation and other N transformations during the course of the experiment are the same for both untreated and treated soils, i.e. that they are unaffected by the application of N.

This is not always the case. In experiments involving the use of ^{15}N labelled fertiliser, it has commonly been reported (but not always; Leitch and Vaidyanathan, 1983) that plants given fertiliser nitrogen take up more unlabelled N than plants receiving no fertiliser. Hauck and Bremner (1976) referred to this phenomenon as a "priming effect". There has been considerable controversy over the cause and interpretation of this effect (Jenkinson *et al.*, 1985).

Jenkinson *et al.* (1985) used the term "added nitrogen interaction" (ANI). According to their theoretical study, ANI's can be either "real" or "apparent". A real ANI can occur if, for example, the added fertiliser N increases the volume of soil explored by the roots. An apparent ANI can occur as a result of isotope displacement reactions or pool substitution. Isotope displacement reactions occur when added N displaces native unlabelled N from a "bound" pool. According to Jenkinson *et al.* (1985) apparent ANI's caused by isotope displacement are only likely to be of significance in exceptional circumstances. Pool substitution, is the process by which added N stands proxy for native N that would otherwise have been removed from the pool. Denitrification and plant uptake of N can under special conditions give rise to pool substitution and thus cause apparent ANI's. However, pool substitution due to microbial immobilisation was considered to be the most important cause of apparent ANI's. With respect to real ANI's, it was concluded that addition of fertiliser N was unlikely to cause large real ANI's by increasing efficiency of uptake; roots showed a limited growth response and even restricted root systems have been shown to absorb the highly mobile NO_3^- ion effectively.

(2) Non isotopic regression method

Where multiple rates of N have been used, crop recovery of applied N can be calculated by linear regression. The slope of the regression between total nitrogen content of the crop and nitrogen applied is taken to represent the proportion of the fertiliser N recovered in the crop. This involves the same assumptions as in the difference method, but is more satisfactory in that less emphasis is placed on the performance of the control plots.

Due to the assumptions used in both of the non isotopic methods, and the consequent fact that the calculated N recovered may actually be derived from sources other than fertiliser, the recovery as calculated is referred to as "apparent N recovery".

Isotopic Methods

^{15}Nitrogen is the heavy isotope of nitrogen occurring naturally in the air at an abundance of 0.3663% of total N_2. It can be concentrated by various techniques and measured by mass spectrometry. ^{15}N can therefore be used as a tracer by enriching N fertiliser and studying enrichment or dilution effects in the plant-soil system.

The use of N isotopes as tracers in biological systems makes three fundamental assumptions:

(i) complex elements in the natural state have a constant isotope composition,

(ii) living systems are unable to distinguish between isotopes of the same element,

(iii) the chemical identity of isotopes is maintained in biological systems.

(3) Isotopic dilution method

In this method, the amount of N recovered by the plant is calculated from the results of total nitrogen and nitrogen isotope ratio (^{15}N:^{14}N) analysis of plant samples from the fertilised plots receiving N labelled with ^{15}N. Control plots receiving no fertiliser are used only to estimate the background ^{15}N level occurring naturally in the sample material.

(4) Isotopic dilution regression method

As with non isotopic methods, where multiple rates of ^{15}N-labelled nitrogen fertiliser have been applied, a linear regression of labelled nitrogen in plants and ^{15}N-labelled nitrogen applied can be used to determine recovery. The regression coefficient representing recovery.

As the labelled N used to calculate recovery is assumed to be solely derived from the labelled fertiliser applied, recovery as calculated by isotopic methods is referred to as "true recovery".

ii) Comparison of Methods

Linear regression of total nitrogen in plants on rates of nitrogen applied (method 2) has given higher values for recovery than linear regression of labelled nitrogen on rates of labelled nitrogen applied (method 4) (Hauck and Bremner, 1976). Comparison of recoveries as given by the two isotope methods (methods 3 and 4), have found them to be similar (Westerman and Kurtz, 1974).

Some workers have reported higher recoveries with the isotope dilution method (method 3) than the difference method (method 1) (Broadbent, 1975; Campbell and Paul, 1978; Broadbent and Carlton, 1980). Others have reported similar recoveries for the two methods (Carter *et al.*, 1967; Olsen, 1980). More usually, recovery as determined by the isotope dilution method, is lower than that given by the difference method (Westerman and Kurtz, 1974; Yoshida and Padre, 1977; Dowdell and Webster, 1980; Dowdell, 1982; Smith *et al.*, 1982; Sah and Mikkelsen, 1983; Bloom, 1987). Jenkinson *et al.* (1985) concluded that the apparent ANI arising as a result of pool substitution due to immobilisation is the most common cause for the lower recoveries.

Neither the difference methods nor the isotope methods give unequivocal results. If a real ANI occurs, recovery measured by the difference method will be in error; if an apparent ANI occurs, recovery as measured by the isotopic methods will be in error. Jenkinson *et al.* (1985) point out that ^{15}N tracer techniques provide a useful tool for following the fate of applied N in the plant-soil system and "extend but do not supplant" non isotopic methods using zero N controls.

iii) Recovery of "Conventional" (soil applied) Fertiliser N

The soil processes of immobilisation, volatilisation, denitrification and leaching affect crop recovery by making fertiliser N unavailable to the crop and have been discussed (Section 2.2.2 and 2.2.3). Crop vigour interacts with these processes and directly or indirectly alters their magnitude. Unfavourable growing conditions, changes in the management of the crop-soil system and changes in fertiliser management influence crop vigour and affect the interrelationships of the nitrogen cycle (Dowdell *et al.*, 1984a).

Prior to the study by Jenkinson *et al.* (1985) of ANI's and the implications of both real and apparent effects for N recovery methods, it was generally accepted that the ^{15}N technique was essential for accurate estimation of N recovery (Westerman and Kurtz, 1974; Fried *et al.*, 1975; Hauck and Bremner, 1976). The ^{15}N technique has therefore been widely used in the last twenty years to calculate recoveries of fertiliser N in the plant-soil system and by difference, to estimate the amount lost. In a number of studies workers have reported recoveries as calculated by the ^{15}N technique and the difference method.

In a review of early ^{15}N work, Kundler (1970) reported a range of 30-70% recovery of applied N by the crop during the year of application, 10-40% recovery in the soils organic matter and losses of between 10-30%. Zamyatina (1971) has reported a similar wide range of recoveries and losses in a review of early work in the USSR. In most cases recoveries in the crop and soil tended to lie in the range 60-65% and 20% respectively, while unaccounted for N tended to be in the order of 20%. Where ^{15}N labelled fertiliser was used in conjunction with lysimeters, between 1 and 5% of the fertiliser N lost was attributed directly to leaching and between 22 to 18% (by difference) to gaseous losses, on sand and clay soils respectively.

Van Cleemput and Baert (1984) have reported crop recoveries of 53%, 59% and 67% for labelled ammonium nitrate applied to winter wheat in the spring at mid tillering, flag leaf and flowering respectively. Fertiliser N recovered in the soil was similar, in the order of 20% in all cases. The large losses associated with the earlier applications were attributed to gaseous losses by volatilisation and denitrification, the latter being considered the most important on the basis of soil type and moisture content at application. No measurements, however, were taken to support this. Vaidyanathan (1984) has reported crop recoveries of 30-72% for labelled N applied to 21 winter wheat crops at different sites.

Crop recoveries of 46-54% in the year of application for 3 rates of labelled N (0, 80 and 120 kg N/ha) applied to spring barley have been reported by Dowdell *et al.* (1984b). Recovery by subsequent crops was very low, total recovery after four years increasing to only 49-57%. This was attributed to slow remineralisation of fertiliser-N in the organic matter. Corresponding apparent N recovery in this study ranged from 38-63% except in one year when N recovery by this method was substantially larger, 67-76%. The unusually low N recovery in the zero-N control was implicated.

Webster *et al.* (1986) used ^{15}N in conjunction with lysimetry to study the fate of spring applications of ammonium nitrate to winter wheat on clay and sandy loam soils at 95 and 102 kg N/ha. Crop recoveries were 46-58% in the first year. Only small recoveries of the labelled N by subsequent crops was recorded over the next 6 years. For the sandy soil, total crop recovery increased to 62%, 23% remaining in the soil. Of the 15% lost, 4% was attributed directly to leaching losses.

Smith *et al.* (1988) have reported recovery in the crop of labelled N applied in spring of 56-80%, according to time of application and previous nitrogen applications. Bloom *et al.* (1988) reporting on experiments over five years at a number of sites and N rates, recorded apparent recoveries ranging from 43 to 88%. In three of the years, apparent N recovery for an application of 200 kg N/ha averaged 58% while recovery determined using ^{15}N averaged 50% (Bloom, 1987). A positive ANI was implicated in respect of this difference.

In a series of experiments between 1980 and 1983 at three sites in SE England labelled N was applied to winter wheat crops in the spring at rates of 47-234 kg/ha (Powlson *et al.*, 1986a;

MacDonald *et al.*, 1989; Powlson *et al.*, 1992). True recovery of fertiliser N in the above ground crop as reported ranged from 39-87% (mean 63%) of N applied, corresponding apparent recovery as <u>calculated</u>, ranged from 30-100% with a mean of 78%. Recovery in the soil was remarkably constant (excluding very low N rates) averaging 18% for N applied as NH_4NO_3 but less (7-14%) where N was applied only as NO_3^-. Where determined, of the labelled N present in the soil to a depth of 70 cm, 84-88% was in the top soil (0-23 cm). On average, only 1.15% (range 0.4-3.6%) of the fertiliser N applied in the spring, was in mineral forms in the soil at harvest (MacDonald *et al.*, 1989).

Loss of fertiliser N from the crop-soil system (0-23 cm), ranged from 4-38% (mean 18%). Powlson *et al.* (1992) showed the magnitude of the loss to be influenced more by weather than by soil type or previous cropping, particularly rainfall in the 3 weeks following application. They also noted a tendency for losses of fertiliser N to be greater when N applied exceeds that required for maximum yield.

In conclusion then from the literature, true recovery of fertiliser N in the above ground crop as determined by ^{15}N-label experiments varies widely, from 30-87% of that applied. Corresponding apparent recovery, where reported, is similarly variable, but generally higher. Recovery of ^{15}N-labelled fertiliser N in the soil, however, is much less variable, invariably around 20% of that applied.

iv) Recovery of Foliar Applied N

There is little information in the literature regarding the recovery of early foliar applications of N sprayed onto the foliage as a substitute for soil applied fertiliser N. A number of experiments have been carried out, however, in which ^{15}N labelled urea has been applied to the foliage around the time of anthesis to increase grain protein content.

The only study with respect to early foliar applications of N was done by Poulton *et al.* (1990). ^{15}N labelled fertiliser was used to assess the benefits of supplying the major part of a winter wheat crop's N requirement as foliar urea rather than conventionally via a solid application of urea ammonium nitrate mixture (UAN) to the soil. On average, foliar and soil applied N were recovered equally by the crop, with 40-46% of the labelled N in the grain and 8-11% in the straw (+ chaff). Less N was recovered in the soil for the foliar urea than the soil applied UAN; 1-11% and 24.5% respectively. Overall therefore, the amount of fertiliser N lost from the crop-soil system was larger (30-40%) for foliar urea than for soil applied UAN (23%). However, the rate of N applied was high (242 kg N/ha), particularly in view of the high soil mineral levels in the spring. The unlabelled foliar urea was also applied at a relatively high N concentration to what would appear to have been a well developed crop; labelled foliar urea applications were made from 9 May to 18 June. Leaf scorch, exacerbated by the use of a wetting agent, was recorded and was implicated in the yield reduction recorded for foliar N compared to soil applied UAN. Further, at harvest, soil samples were only taken to 5 cm on the foliar urea plots compared to 70 cm on the solid fertiliser plots. Any labelled N present in roots or soil below 5 cm would not have been recovered for the foliar urea treatments.

Considering those trials in which foliar urea has been applied as a late season spray to increase grain protein content; Smith *et al.* (1991) working in Australia applied 50 kg N/ha as ^{15}N labelled foliar urea to spring wheat at heading and measured ^{15}N recovery in the plant-soil system and NH_3 loss directly. Recovery in the plant was 69% and in the soil 12%, however, soil samples were only taken to 15 cm. Of the 19% loss by ^{15}N balance, 4% was accounted for by direct measurements of volatilisation. There was evidence to suggest that this was from N washed onto the soil rather than directly from the leaves. The remaining 15% was attributed to losses by denitrification for urea reaching the soil surface either directly during spraying or having been washed off leaves following heavy rainfall.

Powlson *et al.* (1989a) applied 40 kg N/ha as ^{15}N labelled foliar urea (as two 20 kg N/ha dressings separated by 1-2 days) at one of six timings around anthesis to a winter wheat crop which had already received 210 kg N/ha as soil applied ammonium nitrate in spring. At harvest, total recovery of labelled foliar urea in the above ground plant dry matter was between 58-70% of the 40 kg N/ha applied. Recovery was greatest for urea applied at anthesis (GS 65) and least for that applied latest (GS 73). Recovery of urea applied at other timings between GS 39 and 69 were not significantly different. Recoveries in the grain followed the same general trend, with maximum recovery from the anthesis application. Between 30 and 42% of the foliar applied N was unaccounted for. Of this, up to 2% could have been in the stubble which was not sampled. Some of the remaining unaccounted for N would have been in the soil which was not analysed.

It is notable that the first two application dates in this experiment (Powlson *et al.*, 1989a) coincide approximately with the last two application dates of Poulton *et al.* (1990). Powlson *et al.* (1989a) observed no scorch and the recovery of foliar N by the crop for the corresponding spray dates was higher (64-66% c.f. 45-54%).

In an earlier study, Powlson *et al.* (1987a) reported a range in recovery in the harvested crop, between 45-77% (mean 62%) for 30 kg ^{15}N/ha applied to the foliage of winter wheat, half before anthesis (GS 37-39) and half after anthesis (GS 69-73). The crop had previously received sufficient fertiliser-N via the soil in spring to achieve maximum yield. In this experiment, neither chaff nor stubble were sampled, though on the basis of other results (Powlson *et al.*, 1986a) N in chaff and stubble would have probably accounted for less than a further 5% of the labelled N applied. Again no attempt was made to measure ^{15}N in the soil due to the very low label used (1.505 atom % excess ^{15}N).

In both of the latter experiments (Powlson *et al.*, 1987a and 1989a), a greater proportion of the labelled N was recovered in the grain than is normally the case for fertiliser applied to the soil earlier in the year. In both the experiments, volatilisation from leaves was suggested as a probable main cause of loss.

In conclusion, a number of studies with foliar applied urea around anthesis, have indicated that the N is recovered as efficiently by the *crop* as earlier soil applications and a greater proportion of the N is recovered in the grain. Only one study has been reported in which the main soil applied spring N application was substituted for foliar applied urea. While N was recovered by the *crop* as efficiently as soil applied N, overall losses were larger.

2.3 Nitrogen in Crop Production

2.3.1 Yield Response to Nitrogen

i) Conventional Nitrogen Applications

Given the extent of the published work relating to nitrogen in crop production, in no way is this review expected to be definitive. Further, reflecting the title of the thesis, in reviewing the effect of nitrogen and foliar urea on the crop, the emphasis is placed on the physiological basis of the crop response.

Nitrogen is essential for plant growth. It is a component part of essential cell constituents: chlorophyll, nucleic acids, enzymes and the plant cell wall. Nitrogen is not the only vital nutrient; phosphorus, potassium and magnesium and micro-nutrients all play key roles, however, while all nutrients increase the growth and yield of cereal crops, nitrogen has the largest effect and is the key to yield (Addiscott *et al.*, 1991).

The response of cereal yields to fertiliser N is well documented (Sylvester-Bradley *et al.*, 1984a; George, 1984); it generally follows the pattern of diminishing returns (Figure 2.7). Thus while application of fertiliser N commonly doubles cereal yields, the last tenth of the yield requires more than half of the applied N (Sylvester-Bradley *et al.*, 1990b); the implication is of great inefficiency. The optimum nitrogen application (N-opt), the point at which the return from the increase in grain yield is equal to the cost of the extra fertilizer, is often close to the point of maximum yield (Sylvester-Bradley, 1993). The range of N-opt and the rate of response to nitrogen for winter wheat is large, Sylvester-Bradley *et al.*(1984a) report a range of response between zero N and N-opt of 12 to 24 kg grain/kg N. This variation has often been loosely attributed to differences in weather, soil, variety, yield and husbandry factors, however, Sylvester-Bradley *et al.*(1984a) found that the variation in response to N could not be adequately explained by differences in weather or soil N index. Application in excess of N-opt, has consequences for both crop performance and nitrate pollution. Increased N uptake by the plant increases vegetative growth and reduces the mechanical strength of tissues predisposing crops to lodging and attack by insects and fungal disease, and unwanted N is left in the soil increasing the risk of nitrate pollution (Addiscott *et al.*, 1991). The variation in the response to N is greater at higher rates of N applied (George, 1984) and it is likely that this is associated with the increased risk of disease and lodging at higher rates of N.

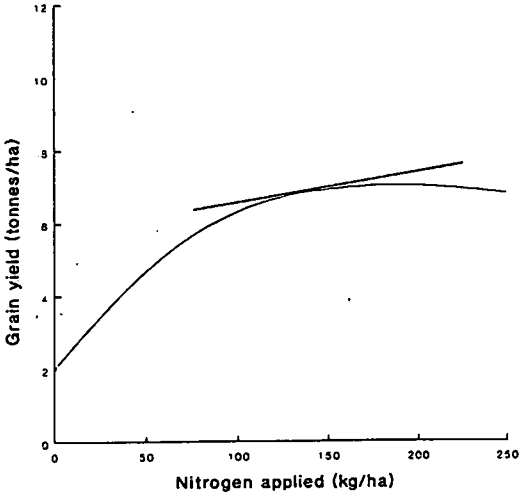


Figure 2.7 Effect of N applied on grain yield (adapted from Addiscott *et al.*, 1991)

ii) <u>Foliar Urea</u>

The majority of experiments reported in the literature refer to the late application of foliar urea, from flag leaf emergence to and after anthesis, applied as a supplement to rather than as a substitute for conventional soil applied N. As with conventional soil applied N, the yield response reported in these studies is highly variable. A number of studies have reported a yield increase (Smith *et al.*, 1987; Lawlor *et al.*, 1989; Dampney & Salmon, 1990; Gardner, 1956; Arnold & Dilz, 1967; Gooding *et al.*, 1991; Penny *et al.*, 1983; Sylvester-Bradley *et al.*, 1984a; Sylvester-Bradley *et al.*, 1990c; Thorne & Watson, 1955), in a large number of experiments no effect on yield has been observed (Pushman & Bingham, 1976; Currie, 1988 (Yugoslavia); Rule, 1987; Smith *et al.*, 1987 and Smith *et al.*, 1991 (Australia), Gooding *et al.*, 1991; Peltonen *et al.*, 1991; Powlson *et al.*, 1989a; Powlson *et al.*, 1987a; Sylvester-Bradley *et al.*, 1984a) and in a minority of experiments a yield reduction has been reported (Dampney & Salmon, 1990; Sylvester-Bradley *et al.*, 1984a and Sylvester-Bradley *et al.*, 1990c). Gooding and Davies (1992) attribute the variation in yield response with late foliar urea to three factors: Time of application has an important effect, on average yield response declines as application is delayed beyond flag leaf emergence. Supply of nitrogen from the soil is also important, response to foliar urea is reduced as the availability of soil nitrogen reserves increases. Finally, leaf scorch and possibly other phytotoxic effects are implicated where yield reductions have been reported.

Few studies have been found in the literature where foliar urea has been used to entirely replace the main N application conventionally applied to the soil at GS 32: In the experiment of Poulton *et al.* (1990), repeated urea sprays (40 kg N/ha x 4) applied between GS 32 and 51 reduced grain yield by 0.69 t/ha compared to 160 kg N/ha applied as a solid urea ammonium nitrate mixture to the soil at GS 32. Scorch, possibly exacerbated by the use of a wetting agent, was implicated in the yield reduction for the foliar treatments. However, the altered timings of application and the use of a mixture of nitrogen fertiliser for the soil applied treatment, may have contributed to the effects. Kettlewell and Juggins (1992) reported no significant difference in yield between fertiliser treatments for 125 kg N/ha applied either as solid ammonium nitrate or as a number of foliar urea sprays between GS 30 and 37, though there was an indication that foliar urea may have reduced yield for those treatments receiving the largest quantity of N in any one foliar spray and for which the most scorch was observed. Warden and Kettlewell (1993) have reported no reduction in yield for up to 210 kg N/ha applied as foliar urea at GS 32 and levels of scorch up to 17%.

2.3.2 Physiological Basis of the Yield Response to Nitrogen

Grain yield of a cereal crop is a function of total biomass production during the growing season and the fraction of the biomass apportioned to the grain (harvest index) (Green, 1984). A consideration of the physiological basis of the effect of N on grain yield can be conveniently divided into its effect on above ground dry matter production and its effect on the partitioning of the dry matter to the grain.

i) Above Ground Dry Matter Production

Gallagher & Biscoe (1978a) demonstrated a strong positive correlation between the rate of dry matter production and intercepted radiation for cereals during the vegetative phase. The implication is therefore, that for a given level of incident radiation, above ground dry matter depends on the fraction of the radiation absorbed by the foliage and the efficiency with which the absorbed radiation is converted to dry matter (Biscoe & Willington, 1984).

The intercepted radiation depends on the green area index (defined as the area of green lamina, sheath and ear per unit area of ground) produced (Monsi & Saeki, 1953). Leaf orientation also affects light interception, however, with the exception of extreme variations in leaf angle, a green area index of 5 is considered optimal for cereals, intercepting 90% of the incident radiation (Sylvester-Bradley & Scott, 1990). It follows then, that the expansion of green leaf area and its persistence governs the amount of light intercepted, and dry matter production will be limited by factors which restrict early leaf growth (until a green area index of 4-5 is reached) and which cause premature and rapid leaf senescence.

For cereals the efficiency of conversion of radiant energy to dry matter is in the order of 1.9 - 2.2 g DM/MJ (Sylvester-Bradley & Scott, 1990). While this efficiency declines as green area is lost and photosynthetic activity reduces during senescence, with the exception of extreme deficiency, nitrogen nutrition has little or no effect on it (Sylvester-Bradley *et al.*, 1990b; Willington & Biscoe, 1984; Green, 1984).

Given the relative insensitivity of the photosynthetic activity of the canopy to nitrogen, it follows that nitrogen affects total dry matter production and grain yield largely by influencing intercepted radiation, due to its effect on leaf area production and persistence.

a) Leaf Area Production

Notwithstanding differences in plant population, leaf area production is governed by: the rate of leaf initiation and appearance, leaf number, the rate of leaf expansion and final leaf size. Nitrogen does not affect the rate of leaf initiation and appearance or the number of leaves on an individual main shoot or tiller, but it increases the size of individual leaves (Puckeridge, 1963; Milthorpe & Moorby, 1979; Biscoe & Gallagher, 1978; Willington & Biscoe, 1984; Sylvester-Bradley *et al.*, 1990b; Sylvester-Bradley & Scott, 1990). Nitrogen increases leaf size by increasing the rate of leaf expansion (Gallagher, 1976; Biscoe & Gallagher, 1978; Sylvester-

Bradley & Scott, 1990) and Sylvester-Bradley *et al.*(1990b) have implied that this may be a direct effect of increased water content of the tissues, associated with increased N uptake, causing the tissues to expand.

While N does not affect the number of leaves per stem, it does affect tillering and thereby affects stand leaf number. The effect of nitrogen on tillering depends on time of application. Early nitrogen (applied before or during tillering) increases tiller number by increasing both tiller production and survival (Langer, 1980; Darwinkel, 1983; Garcia de Moral *et al.*, 1984; Nair & Chatterjee, 1990; Sylvester-Bradley & Scott, 1990; Biscoe, 1979). Late N, applied at stem extension, increases tiller survival but has no effect on tiller production at the normal time (Gallagher & Biscoe, 1978b; Willington & Biscoe, 1984; Sylvester-Bradley & Scott, 1990; Darwinkel, 1983). The effect of N on tillering has a greater influence on green area index than its effect on leaf expansion (Spiertz *et al.*, 1984; Sylvester-Bradley *et al.*, 1990b).

b) Leaf Area Persistence

The persistence of leaf area influences the time during which radiation can be absorbed. As most of the carbohydrate in grain is produced by photosynthesis after ear emergence, it is to be expected, that grain yield is closely correlated with photosynthetic area present after ear emergence. Leaf area duration (LAD), the integral of leaf area index with time, takes account of both leaf area and its persistence, and LAD from ear emergence to maturity has been shown (for leaf area indices at anthesis up to the optimum), to be closely correlated with grain yield (Thorne, 1973).

Leaf area persistence is determined by the onset of senescence and the rate of senescence. The rate of senescence is accelerated in crops which are deficient in N. This has been attributed to the translocation of N from fully expanded leaves, to meet the demand for nitrogen by rapidly growing vegetative parts and the grain that cannot be met by absorption through the roots, leading to general disruption of the leaf cells (Milthorpe and Moorby, 1979). Application of fertiliser N has been shown to delay senescence (Thorne and Watson, 1955; Spiertz and Ellen, 1978; Ellen and Spiertz, 1980). Sylvester-Bradley *et al.* (1990b) have suggested that the size of the crop's canopy is directly proportional to the amount of N it has been able to acquire; for cereals 30 kg N are required to produce 1 hectare of green surface.

c) Foliar Urea and Dry Matter Production - A Physiological Basis

In the context of the physiological basis of the effect of N on above ground dry matter production, the rationale to date for the use of foliar urea is the supply of supplementary N to delay senescence and increase green area index. A report by Garcia and Hanway (1976) in the USA, that a foliar urea spray incorporating P, K & S applied to soya bean during the seed filling period increased yield, prompted further work. However, Below *et al.* (1984a&b and 1985) working with maize reported that foliar applications of a complete nutrient mix containing urea or urea alone, did not delay senescence and no effect on stover weight or grain yield was recorded. Hageman and Below (1990) citing Thomas and Stoddart (1980), suggest a possible explanation as to why the supplementary foliar urea applications fail to maintain photosynthetic activity in these studies. They note that for some plant species the chloroplast genome appears to become non-functional at the time the leaf reaches full expansion. The chloroplast genome provides the template required for the synthesis of ribulose bis-phosphate carboxylase (RuBPcase). If the maize genome becomes non-functional at the time of full leaf expansion no further RuBPcase can be synthesised thereafter. If this is the case, then application of supplementary foliar N to maintain photosynthetic activity will not be successful until a technique is found that will derepress the chloroplast genome.

More recently, however, Lawlor *et al.* (1988 and 1989) have reported that foliar urea applied to winter wheat after flag-leaf emergence but before ear emergence, delayed senescence and prolonged photosynthetic activity by about one week and an increase in grain yield was recorded. The reason for the positive response observed in this study compared to those with maize may be due to the chloroplast genome in wheat continuing to be active after the flag leaf has reached full expansion.

The observation by Sylvester-Bradley *et al.* (1990b) that the size of the crop's canopy appears to be directly proportional to the amount of N it has been able to acquire may provide a more novel rationale for the use of foliar N. Physiologically it may be more efficient to match nitrogen applications to the crop's requirement for canopy growth rather than supply the bulk of the N as a single or split dressing as is currently recommended. This could be achieved by supplying smaller amounts of N more frequently but at specific times to produce the optimum green area index. Foliar N may be a more efficient method of supplying N for this purpose during the late spring and early summer when dry soils would prevent the uptake of solid N fertilisers. However, in the experiment of Poulton *et al.* (1990), supplying the bulk of the nitrogen requirement of winter wheat as foliar sprays rather than as a soil application, reduced total above ground dry matter at harvest and grain yield. This may have been attributable to severe leaf scorch caused by the foliar sprays, which would have reduced green area index.

ii) The Effects of Nitrogen on Dry Matter Partitioning

The previous section considered the physiological basis of the effect of N on above ground dry matter production in relation to its effect on grain yield and reviewed reports in the literature relating to foliar applied N in this respect. In determining final grain yield, the partitioning of the above ground dry matter between the grain and other parts of the plant is important. The ratio of grain yield to total dry matter yield is called the harvest index (HI) (Donald and Hamblin, 1976). It follows, that the harvest index will be affected by factors which influence above ground dry matter production and grain yield to a different extent. In this section the effect of N on the components of grain yield will be considered first, and than the effect of N on these components relative to above ground dry matter production, i.e. the effect of N on harvest index.

a) The Effect of N on the Components of Grain Yield

The components of grain yield can be considered as the product of the number of ears per unit area, the number of grains per ear and the average grain weight (Thorne, 1966). No single yield component predominates in determining yield. However, Gallagher and Biscoe (1978b) noted that a large number of grains per unit area (the product of ear number and grain number per ear) were correlated with large yields.

The effect of N on tillering has already been outlined in the context of the effect of tillering on leaf number. Nitrogen increases the production and survival of tillers and therefore the number of ears per unit area.

Nitrogen increases the number of grains per ear, but the effects tend to be smaller than the effect on ear population. Grain number per ear is a function of the number of fertile spikelets per ear and the number of grains per fertile spikelet. Nitrogen increases the number of spikelets per ear, the effect has been shown to be due to increased rate of spikelet initiation with little effect on duration (Whingwiri and Kemp, 1980; Whingwiri and Stern, 1982). Nitrogen is most effective at increasing spikelet production when applied during tillering at or close to the double ridge stage (i.e. close to the start of spikelet initiation), later applications, from floret initiation to ear emergence, increase the number of grains per fertile spikelet (Langer and Liew, 1973; Darwinkel, 1983; Single, 1964). The effect of nitrogen on grains per fertile spikelet could be due to effects on floret production and/or floret survival. However, floret production, unlike spikelet production, has not been found to be affected by nitrogen (Langer and Hanif, 1973; Whingwiri and Stern, 1982). The implication therefore, is that nitrogen applied around terminal spikelet increases grains per fertile spikelet by reducing floret abortion. Spikelet death is also likely to be reduced.

Grain weight is determined by the supply of assimilate from current photosynthesis or from storage during grain fill. While as noted, nitrogen fertiliser increases leaf area duration and therefore may be expected to increase grain weight, it also increases grain set. Ultimately, the effect of nitrogen on grain weight will depend on its effect on these parameters relative to each other i.e. source / sink relationships within the plant in particular on green area duration per grain (Hay and Walker, 1989). In practice, nitrogen application has either little effect on grain weight (Batey and Raynish, 1976; Evans, 1977; Gallagher *et al.*, 1975) or results in modest reductions at higher rates of N applied (Watson, 1936; Batey and Reynish, 1976; Batey, 1976; Dyson, 1977; Pearman *et al.*, 1978), due to increased competition for carbohydrate supply from increased grain numbers. Of the three yield components, grain weight is generally conservative (Green, 1984) and while the above effects on grain weight are noted, grain weight is less affected by nitrogen than ear population or grains per ear (Nair and Chaterjee, 1990).

b) Effect of Nitrogen on Harvest Index

While N can potentially increase all of the yield components, given that harvest index is the ratio of grain yield to above ground dry matter, the effect of N on harvest index depends upon its effect on the components of yield relative to its effect on above ground dry matter production.

Donald and Hamblin (1976) in a review of the subject, report that application of N to cereals commonly gives an increase in above ground dry matter production and a corresponding decrease in harvest index, they also note the interaction of nitrogen with water in its effect on harvest index. They report that in investigations where soil water was adequate, N application increased above ground dry matter production and decreased harvest index, however, the percentage increase in above ground dry matter production exceeded the percentage decline in harvest index and an increase in grain yield was recorded. When water supply is limited, however, the decrease in harvest index associated with N application is more marked and can exceed the increase in above ground dry matter production, and grain yield is reduced. The interaction between water and nitrogen application on harvest index is attributed to the increased vegetative growth causing depletion of water reserves with the consequent negative effects on the yield components. The decrease in harvest index due to N when water is not limited, is attributed to the effect of heavy vegetative growth on light relationships within the canopy adversely affecting ear initiation and grain development.

In a more recent review of the subject, Hay (1995) reported that N application up to N-opt generally has little effect on harvest index, but use of super optimal rates of N tend to cause small but significant reductions in harvest index. A consideration of the data cited by Donald and Hamblin (1976) regarding the effect of N on harvest index where water supply was not considered to be limited, indicates that the greatest reductions in harvest index only occurred at rates of nitrogen applied over what would have been considered to be optimal for the site <u>at the time</u>. Hay (1995) also notes that from a range of investigations, there is no indication that timing of N application affects harvest index. This is surprising, later N applications around terminal spikelet increasing the number of grains per spikelet as noted earlier, with little effect on vegetative growth relative to early (tillering) applications, should increase harvest index. Thorne and Wood (1982), have reported that winter wheat crops given N later (mid April) had higher harvest indices than those given N earlier (early March), due to reduced leaf and stem dry matter production at and after anthesis. Consideration of the investigations cited by Hay (1995) (McLaren, 1981; Darwinkel, 1983; Peltonen, 1992), shows that harvest index did generally increase with later applications of N, however, the magnitude of this increase was small and statistically significant only in a few instances.

Effectively then, N increases above ground dry matter production at the expense of the yield components and harvest index is reduced, and the effect is more marked where water supply is limited. Up to N-opt, the reduction in harvest index is limited, at super optimal rates of N the reduction is still small but is significant. Further, the effect of N timing on harvest index is limited.

The effects of N on harvest index as reviewed here, are in accordance with the observation that under normal conditions the harvest index of wheat and barley is generally conservative and does not vary systematically with yield (Gallagher and Biscoe, 1978b). It follows then, that the effect of N on grain yield is mainly a reflection of its effect on above ground dry matter production, harvest index being relatively constant. The linear relationship between grain yield and total dry matter production is a generally recognised phenomenon (Green, 1984; Biscoe and Willington, 1984).

c) Effect of Foliar Urea on the Components of Yield and Harvest Index

While a number of reports can be found in the literature regarding the effect of foliar urea on the components of grain yield, few consider the effect on grain yield in relation to total dry matter production i.e. harvest index. Reference to the effect of foliar urea on harvest index is therefore limited to those investigations where it was recorded, or where sufficient data is reported to permit its calculation. Most of the references cited here refer to the application of foliar urea to supplement the main N application rather than as a substitute for it, reflecting interest to date in the use of foliar urea as a late N supplement.

All yield components have been reported to be influenced by foliar urea according to time of application. A review of the effects of foliar urea on yield components and harvest index is therefore most logically considered according to time of application.

Early applications of foliar urea, during and at the end of tillering, have been reported to influence ear number and grains per ear: Hanley *et al.* (1966), in some early work reported that

50 kg N/ha as urea sprayed onto the foliage during tillering had no effect on ears/m^2 but significantly increased the number of grain bearing spikelets per ear compared to zero N plots. Compared to N applied as a solid at the same time, however, yield responses were inferior, due to the soil applied N increasing the ears/m^2. All N treatments caused small reductions in grain weight. Sarandan and Gianibelli (1990) in Argentina reported that 20 kg N/ha applied at the end of tillering increased grain set due to increased ears/m^2 and grain number/ear. The number of spikelets per ear was not affected, the implication is therefore an effect on floret number per spikelet. Grain weight was not affected. Grain yield, above ground dry matter and harvest index were all increased, indicating more efficient partitioning of the dry matter to the grain.

Foliar urea applications at flag leaf and anthesis have been reported to influence grain number per ear and grain weight: Peltonen (1992) investigated the effect of a supplementary 20 kg N/ha applied as foliar urea over four stages of ear development under glasshouse conditions. Maximum effect of foliar urea on floret numbers was recorded for N applied around GS 39 and this was reflected in an increase in grain number per ear and grain yield at harvest, above ground dry matter also increased and no effect on harvest index was recorded. Supplementary foliar urea applied at anthesis significantly increased harvest index compared to foliar urea applied at GS 22, this was associated with an increase in grain weight, with no significant effect on grain number per ear. Sadaphal and Das (1966) in India, have reported that foliar urea sprays applied at ear emergence and anthesis increased grain number per ear and grain weight. The increase in grain yield was not supported by a corresponding increase in total dry matter, and harvest index therefore increased. Arnold and Dilz (1967) reported a positive effect on yield of applying 11 kg N/ha as foliar urea just prior to or at ear emergence. The yield increase was associated with an increase in the number of grains per ear, a slight reduction in grain weight was recorded. Strong (1982) in Australia, reported that the increased grain yield for foliar urea applied at booting was due to increased grain number per ear and grain weight, though the latter was not significant. Similar responses were observed for N applied to the soil at the same time, though this was likely to be attributable to good soil water relations at the time the solid N was applied; irrigations were timed to follow applications. However, yields were still below those where all of the N was applied at planting. Lawlor *et al.* (1989) reported increased grain yield due to about equal increases in grain number and weight, for 40 kg N/ha applied as foliar urea after flag leaf emergence prior to ear emergence and Penny *et al.* (1983), have reported a positive effect on grain weight of 50 kg N/ha applied as foliar urea at ear emergence and anthesis. In contrast to these positive effects, however, Peltonen *et al.* (1991) found no significant effect on grain number per ear or grain weight of 20 kg N/ha applied as foliar urea at heading and Powlson *et al.*, (1987a and 1989a) reported no effect on grain weight of foliar urea applications at flag leaf to just after anthesis. Gooding (1988) has reported contrasting effects on grain weight and grain number in two successive years for foliar urea applied between flag leaf emergence and anthesis; yield effects appeared to be largely related to effects on grain number.

In the experiment of Poulton *et al.* (1990), in which substitution of the main soil application with foliar urea applications applied between GS 32 & 51 resulted in a reduction in grain yield, no data on the effects on individual yield components was presented. However, the reduction in grain yield was accompanied by a proportional decrease in total dry matter production and harvest index was unaffected.

Foliar urea applied at anthesis has been reported to influence grain weight. Strong (1982) and Smith *et al.*(1987) have reported anthesis applications to increase grain weight, however, Pushman and Bingham (1976) reported no such effect. Later applications, after anthesis, usually have no effect on grain yield or its components (Strong, 1982; Sarandan and Gianibelli, 1990).

2.3.3 Uptake of Foliar Urea

i) Mechanisms and Pathways of Uptake

In order to enter the cells of the leaf, foliar applied nutrients must cross the cuticle, cell wall and plasma membrane of the epidermal cells. The cuticle is non-living and usually consists of an outer layer of cutin and wax and an inner layer of cutin, wax and cellulose, though additional layers have been reported in some leaves (Kannan, 1986a). Originally it was considered that stomata provided a means by which nutrient solutions may cross the cuticle, however, the walls of the stomatal opening and cavity are also covered with cuticle and further, the stoma are filled with gas and a high pressure would be needed to displace this (Franke, 1986). It is now considered that nutrient solutions cross the cuticle via gaps in the outer wax layer and then via intermolecular spaces within the cuticle proper, free hydrophilic hydroxyl and carboxyl groups projecting into the intermolecular spaces facilitating the passage of water and substances dissolved in it (Franke, 1986). Larger pores and channels are present in the cuticle through which wax is extruded to the outer surface, but these are not considered to serve as a pathway for the transport of solutes (Kannan, 1986b).

According to Franke (1986), absorption does not take place throughout the entire cuticle but at localised areas on it. He notes that these coincide with the position of ectoteichodes which project into the cuticle from the cell wall below, and concludes therefore that a preferred area for penetration of the cuticle exists above an ectoteichode. Trichomes, hair-like projections of the epidermis, have also been implicated in increasing the permeability of the cuticle, their movement disrupting the physical arrangement of the wax (Schönherr and Bukovac, 1970). Further, stomata while not providing a direct means of access across the cuticle may be indirectly involved; permeability through stomatous cuticles is generally easier than through astomatous ones, it has been suggested that this may be due to the cuticle being thinner where it covers the stomatal cavity (Kannan, 1986a).

The mechanism of uptake of nutrient solutions across the cuticle is by diffusion from a high concentration on the outside to a low concentration in the intermolecular spaces of the cuticle and interfibrillary spaces of the cell wall (Kannan, 1986a). In addition, there is evidence for the facilitated diffusion of urea, urea has been reported to alter the bonding between the macro molecules of the cutin increasing the permeability of the cuticle (Yamada *et al.*, 1965).

The wall of the epidermal cell beneath the cuticle consists of a mixture of cellulose, pectin, hemi-cellulose and some waxes and its structure is that of inter linked fibrils (Franke, 1986). The interfibrillary spaces have a diameter down to 0.01 μm and are continuous with each other, as such the cell wall is permeable to water and solutes and movement across it takes place by diffusion as in the cuticle (Franke, 1986).

Franke (1967) implicated specialised plasmitic structures called ectodesmata or ectoteichodes in the transport of solutes across the cell wall, however, Schonherr and Bukovac (1970) dismissed these as artifacts of the staining technique used. Franke later agreed (Franke, 1971) that these bodies were not morphological entities, but rather hollow spaces in the cell wall. Given the permeable structure of the cell wall as outlined above, Kannan (1986a) concludes that ectodesmata, even if present, would be of little significance with regard to permeability. The presence of such structures in the cuticle, however, would aid permeability, and Franke (1967) has depicted ectodesmata as forming a continuum from below the epicuticular wax across the cuticle and cell wall and considers that they facilitate the entry of solutes across the cuticle as well as the cell wall (Franke, 1971).

The plasma membrane represents the final barrier to the uptake of nutrient solutions. It is semi-permeable and thus only small water molecules can penetrate it by diffusion (Franke, 1967). Transport of solutes across the plasma membrane takes place by active transport, the energy required derived from photosynthesis or respiration (Kannan, 1986b).

ii) Rate and Pattern of Uptake

There are abundant reports in the literature that foliar urea is rapidly taken up following application. Foliar uptake has been inferred, but not proved, by monitoring depletion of foliar applied urea from the leaf surface. Using this technique Bowman and Paul (1989, 1990a, and 1992) in the USA have reported for a number of grass species in a controlled environment, that between 55 and 70% of the applied N is taken up within 48 hours; and Bowman and Paul (1990b) have reported uptake of 80 to 100% of applied N within 48 hours for Kentucky blue grass turf under field conditions. In all cases the pattern of uptake characteristically followed an initial phase of rapid uptake during the first 12 hours followed by a slower rate of uptake thereafter. Rapid uptake during the first few hours following application has also been reported for a number of horticultural crops in glasshouse studies in the USA (Cook and Boynton, 1952;

Cain, 1956; Impey and Jones, 1960). Foy *et al.* (1953) in the USA and Lawlor *et al.* (1988) in the UK have reported the rapid disappearance of foliar applied urea from maize and wheat leaves respectively in the field.

More direct evidence of foliar uptake has been provided by monitoring the accumulation of ^{15}N in the plant following applications of ^{15}N labelled foliar urea. Using this technique Bowman and Paul (1989, 1990a and 1992), have reported rates of uptake under controlled conditions of 43% in 48 hours for Kentucky blue grass, 55% in 72 hours for creeping bent and tall fescue grass on average and 35% in 48 hours for perennial rye grass. The authors also reported that in a comparison of techniques, the depletion method significantly over estimated uptake compared to ^{15}N technique. Below *et al.* (1985) in the USA reported 32% absorption within 24 hours for foliar urea applied to maize 7 days after anthesis using ^{15}N labelled urea, and in Australia Smith *et al.* (1991) have reported 68% absorption 4 hours after application for foliar urea applied to wheat at anthesis. Even in these studies, however, the results are not definitive; in the study of Smith *et al.* (1991) a proportion of the foliar N was washed off the leaves onto the soil after heavy rainfall and in the other studies urea N reaching the soil and subsequent uptake by the roots cannot be precluded.

Glasshouse and field studies with fruit trees in the USA have shown that urea is generally absorbed more rapidly by young leaves than older leaves, and that absorption is most rapid from the lower than the upper leaf surface (Cook and Boynton, 1952; Cain, 1956; Impey and Jones, 1960; Klein and Weinbaum, 1985).

iii) Volatilisation Losses

Nitrogen losses by volatilisation are a particular problem of urea fertiliser and occur when urea undergoes hydrolysis to $CO_2 + NH_3$ in the presence of urease.

Bowman *et al.* (1987) in the USA reported losses of N as high as 36% for N applied as foliar urea to Kentucky blue grass turf in the field and found that this could be substantially reduced by irrigation. In a subsequent study using increased spray volumes smaller losses, 5-12%, were reported (Bowman and Paul, 1990b). Repositioning of the urea deeper in the canopy was suggested as an explanation for the reduced losses in both cases. Poulton *et al.* (1990) in the UK implicated volatilisation losses as a possible reason for the lower overall recovery of N associated with the application of the main spring N dressing to winter wheat as foliar urea compared to soil applied urea ammonium nitrate. Powlson *et al.* (1987a and 1989a) again in the UK, have also suggested volatilisation from the leaves as a probable main cause of loss for late applications of N as foliar urea applied to winter wheat around ear emergence and anthesis.

While these studies have suggested volatilisation as being implicated in N losses from foliar urea applications, few workers have actually measured volatilisation from foliar applied urea under field conditions. Smith *et al.* (1991) in Australia recorded only 4% of the N applied to wheat as foliar urea lost as ammonia and suggested that this came from urea that had reached the soil surface.

2.3.4 N Recommendation Systems

i) Amount of N

All current nitrogen recommendation systems can be viewed in terms of a balance sheet representing the nitrogen requirement of the crop on the one hand and the nitrogen potentially available from the soil on the other, any deficit being made up from fertiliser nitrogen. This most obviously applies to the French system (Viaux, 1984) and cruder versions of the balance sheet approach are used elsewhere in Europe and the UK. (Sylvester-Bradley *et al.*, 1987).

The N recommendation system currently employed in the UK (MAFF, 1994b) can be considered as a single guideline dressing modified to take account of:

(i) - expected N residue due to the previous crop (accounted for by the site nitrogen index),

(ii) - expected over-winter survival of the residue (accounted for by soil type and over-winter rainfall),

(iii) - expected soil nitrogen supply from mineralisation (accounted for by soil type),

(iv) - expected overall crop demand for nitrogen (implied in the prediction of yield).

Webb *et al.* (1995) and Webb and Sylvester-Bradley (1995) have recently produced evidence indicating that the adjustment of economic fertiliser recommendations according to anticipated yield ((iv) above) may not be justified; in a series of experiments they found little evidence that N-opt is dependant upon grain yield, much of the variation in response to fertiliser N being due to site specific factors.

Measurement of the potentially mineralisable nitrogen, or at least the measurement of soil mineral nitrogen in the spring, as is required by most other recommendation systems is not used in the UK system. This is due to the fact that past experimentation has shown no correlation between these measurements and a variety of response predictors, including optimal N and rate of response to N (Needham, 1984). The lack of success of these measurements in the UK in predicting optimum N requirement has been attributed to the wider range of soils and greater variability of the weather, particularly in the spring, compared to those countries where they form a successful part of the recommendation system (Needham, 1984). Addiscott and Darby (1991) have inferred that insufficient sampling depth and too wide a spread of sampling dates (in the experiments considered), as likely reasons why the amount of soil mineral N may fail as a predictor of N-opt in the UK and further, showed that values of N-opt could be related satisfactorily to the computed values of soil mineral N for appropriate depths on single dates. More recently Harrison (1995), has demonstrated a statistically significant relationship between soil mineral N in the autumn or spring and N-opt for winter cereals, and has noted the importance of depth of sampling according to the method used to predict N-opt: if coefficients fitted by linear regression are used to express the effect of soil mineral N at different depths a stronger relationship between N-opt and soil mineral N is obtained when all sampling depths to 90 cm are utilised, however, if soil mineral N is assumed to substitute on a 1:1 basis for fertiliser N, a stronger relationship is obtained between N-opt and soil mineral N by inclusion of soil mineral N only in the 0 to 30 cm depth. Further, it was noted that whichever approach is taken to estimate N-opt, the amount of variation in N-opt accounted for after taking into account soil mineral N can be related to differences in mineralisation from previous crop residues, organic manures and native organic N occurring after soil mineral N measurement in the autumn or spring. Failure to make allowance for such differences between sites, reduces the amount of variation in N-opt accounted for considerably. The results suggest that mineralisation after soil sampling in the spring can provide up to 100 kg N/ha on high residue sites. Recently there has been a renewed interest in the UK in the use of soil mineral N measurements in the spring in predicting crop N requirements, particularly in such "high fertility situations" (Chambers, 1992b; Paulson, 1994). N recommendations based on soil mineral N determination are likely to be most effective in these situations.

Measurements made on the growing crop have also been used to predict N requirements and monitor the N status of the crop. The recommendation system developed by Moller Nielsen (1985) uses the N content of the crop in the spring to predict the fertiliser N required, and stem nitrate is used as a guide to N fertiliser application to wheat and barley in West Germany (Wehrmann *et al.*, 1987). N content of the crop dry matter in the spring (Batey, 1984) and nitrate concentrations in the stem sap (Widdowson *et al.*, 1984) have been tested successfully in the UK as a measure of the N status of the crop. The measurement of nitrate reductase activity in cereal leaves as a measure of soil N status and crop N requirement has also been tested, but conclusions as to its usefulness are conflicting (Sylvester-Bradley *et al.*, 1984b and Verstraeten & Vlassak, 1984).

ii) Time of Application

Time of N application, within limits, has less effect on yield than the amount of N applied (Needham, 1984). Current recommendations for the timing of N application to winter cereals reflect the N uptake by the crop. N uptake in winter cereals is characterised by a phase of very slow uptake from sowing to the start of stem extension, followed by a phase of very rapid uptake from stem extension to heading (Widdowson *et al.*, 1987). Rates of uptake prior to stem extension are usually less than 0.2 kg N/ha/day while average rates of uptake after stem extension of 1.5 kg N/ha/day are typical (data from Widdowson *et al.*, 1987), though higher maximum rates, up to 5 kg N/ha/day, have been reported (Barraclough, 1986).

In accordance with this, application of N in the seedbed for winter cereals is not recommended and the most important stage for N application is early stem extension. Current recommendations for timing of application are given in detail by MAFF (1994b). Although timings are specified primarily by growth stage, constraints of calendar dates are incorporated to avoid early application of N to advanced crops before drainage ceases in the spring, and late applications of the main treatment to backward crops which may not reach stem extension until mid May when soil conditions may be very dry.

Attempts have been made to increase yields by application of N to coincide with certain "critical stages" of plant development identified by differentiation of the stem apex, however, the results suggest little advantage of such precise timing of application compared to standard recommendations (Sylvester-Bradley *et al.*, 1987).

In summary then, grain yield response to N is well documented. Effects on yield are largely due to effects on above ground dry matter production, due to N increasing green area index owing to effects on shoot production and survival and leaf size. The effect of N on partitioning of the dry matter to the grain is limited, however, the potential of later N applications, by increasing spikelet and floret survival, has been noted in this respect. Effects of solid and foliar N reported in the literature have been reviewed in this context. Uptake of foliar urea takes place by diffusion across the cuticle and epidermal cell walls of the leaf. The potential for N losses by volatilisation prior to uptake has been noted. Current N recommendation systems attempt to balance potential N off take by the crop and N supply from the soil with fertiliser N. Timing of fertiliser N according to these recommendations is largely related to rate of uptake of N by the plant, and within reason has little effect on yield.

3.0 MAIN EXPERIMENT

3.1 MAIN EXPERIMENT 1992

The aim of this project as stated previously, is to investigate the physiological consequences of foliar urea applications and effects on nitrate leaching as a basis for the rational development of a more environmentally acceptable method of nitrogen fertiliser application to winter wheat.

Supplying a proportion of the total fertiliser N requirement of a wheat crop through the foliage would potentially reduce immobilisation of fertiliser N in the soil organic matter, or losses by leaching or denitrification in the soil. Only one study has been found in the literature where foliar urea has been used to replace the main N application conventionally applied to the soil around GS 32. Poulton *et al.* (1990), compared repeated urea sprays (40 kg N/ha x 4) applied between GS 32 and 51 with 160 kg N/ha applied to the soil as urea ammonium nitrate mixture at GS 32. A reduction in grain yield and a larger amount of unaccounted for fertiliser N were recorded for N applied as foliar urea. These results, however, may have been attributable to leaf scorch and / or differences in timing of application of N in relation to plant development: a single rate of foliar urea was applied at a relatively high N concentration to a well developed crop and leaf scorch, possibly exacerbated by the use of a wetting agent, was observed.

The objectives of the first year study were therefore:

1) To set up a field experiment to be repeated on the same site over three years to compare supplying the main spring nitrogen application as different proportions of foliar urea rather than as conventional soil applied ammonium nitrate or urea.

2) To measure yield and above ground dry matter production at harvest, to establish the physiological basis of any yield differences in terms of harvest index and dry matter production.

3) To measure apparent nitrogen recovery in the above ground crop at harvest.

4) To measure soil water nitrate concentrations during the following winter, to estimate N leaching losses.

3.1.1 Field Treatments

Winter wheat (*Triticum aestivum* cv. Riband) was drilled into a sandy loam soil (Bridgnorth series) on Little Pipe Strine field at Tibberton Manor Farm, Edgmond, Shropshire on 13 October 1991. The site had been in continuous wheat since 1981 receiving 215 kg N/ha per year as fertiliser N according to standard farm practice, with no organic manure applied. Seedbed cultivations consisted of straw incorporation by ploughing to 20 cm followed by pressing and a Roterra type cultivation. C2 seed treated with Baytan seed dressing was drilled using a combination drill with a row spacing of 10 cm. Seedbed fertiliser consisted of 37 kg/ha phosphate (P_2O_5) and 56 kg/ha potash (K_2O). Nitrogen treatments in spring were as shown in Table 3.1.

Table 3.1 Nitrogen treatments in the main experiment

Trt. No.	N in early March (kg N/ha)		N at GS 31 (kg N/ha)		Total N (kg/ha)
	Rate	Form	Rate	Form	
1	0	-	0	-	0
2	50	Solid ammonium nitrate	120	Solid ammonium nitrate	170
3	50	Solid urea	120	Solid urea	170
4	50	Solid urea	90 30	Solid urea Foliar urea	170
5	50	Solid urea	60 60	Solid urea Foliar urea	170
6	50	Solid urea	30 90	Solid urea Foliar urea	170
7	50	Solid urea	120	Foliar urea	170
8	50	Foliar urea	120	Foliar urea	170

The experiment consisted of 32 plots arranged in four randomised blocks. Plots were 4 m by 10 m, adjacent blocks separated by a 4 m wheeling (Figure 3.1, Plate 1).

Solid ammonium nitrate (Nitram 34.5% w/w) and solid urea (Seabright 46% w/w) were applied to the plots by hand. The foliar urea was applied as Nufol (20% w/v; NUFOL, Hydro Chafer Ltd., York) at 30 kg N/ha in 300 l/ha i.e. 150 l Nufol + 150 l water. The second spray in early March for treatment 8 was applied as 20 kg N/ha in 200 l i.e. 100 l Nufol + 100 l water. The objective was to apply 30 kg N/ha every four to five days starting at GS 31 to give the required rate of N as foliar urea according to treatment. In practice, intervals between successive sprays were longer due to prevailing weather conditions. Actual dates and growth stages of applications are given in Table 3.2. Foliar applications were not made to wet leaves or when rain was imminent. All foliar urea applications were made through flat fan nozzles using an Oxford precision sprayer (MDM Engineering Ltd. Southampton).

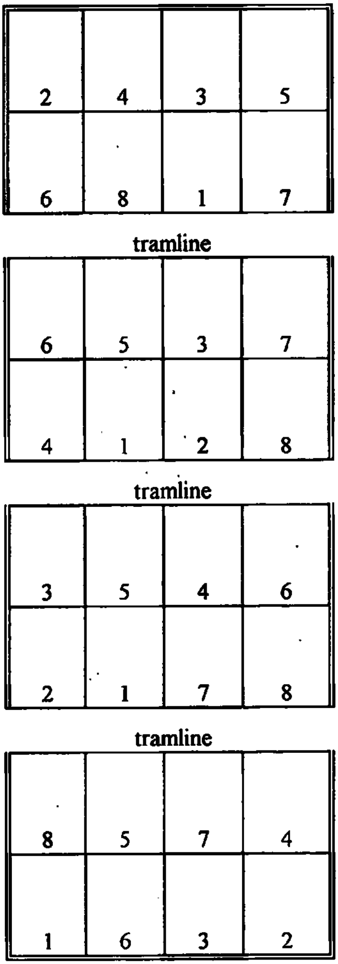


Figure 3.1 Plot layout and randomisation in the main experiment (numbers refer to treatments, refer to Table 3.1)

Plate 1

Plate 2

Plates 1 and 2 Main experiment site at Little Pipe Strine after drilling and installing ceramic cups in the autumn and at GS 32 in the spring

Table 3.2 Dates of N applied in the main experiment 1992

		TREATMENT							
ZGS	Date Applied	Zero-N	NH_4NO_3 (kg N/ha)	Solid urea (kg N/ha)	30 kg N/ha Foliar urea	60 kg N/ha Foliar urea	90 kg N/ha Foliar urea	120 kg N/ha Foliar urea	170 kg N/ha Foliar urea
< 30	17/3		50	50S	50S	50S	50S	50S	30F
< 30	25/3								20F
31	20/4		120	120S	90S	60S	30S	30F	30F
					30F	30F	30F		
32	5/5					30F	30F	30F	30F
33	14/5						30F	30F	30F
37	19/5							30F	30F
Total		0	170	170	170	170	170	170	170

S = Urea applied as solid F = Urea applied as foliar spray

3.1.2 Sampling and Analytical Techniques

Scorch

On 22 May 1993, three days after the final foliar urea application, leaf scorch for treatments 5, 6, 7 and 8 was assessed by subjectively scoring the necrotic area due to scorch on the youngest fully expanded leaf for twenty randomly selected plants per plot. Mean values per plot were calculated for statistical analysis.

Above Ground Dry Matter at Harvest

On 22 July, the plants from two adjacent 0.25 m lengths of row were removed at soil level from two positions in each plot. The samples were bulked and the whole plant material dried at 80^0C for 48 hours. Total above ground dry matter was calculated using the row width to determine the sampling area.

Above Ground Plant N

For each plot, 15 randomly selected whole plant stems from the dried sample were ground using a Cyclotec 1093 sample mill (mesh size 1 mm) and above ground whole plant N determined in duplicate by the Kjeldahl method (Bremner 1965a) using a Kjeltec Auto 1030 Analyzer. A separate dry weight determination was carried out for each sample at the time of analysis and the results adjusted to zero percent moisture content. Apparent recovery of fertiliser N in the above ground dry matter for each plot was calculated by subtracting above ground N in the zero N control plot (in the corresponding block) and dividing by the fertiliser N applied.

Straw and Chaff C/N Ratio

The C/N ratio for straw and chaff returned to the field after harvest was determined for each plot. The ears were separated from 15 randomly selected whole plant stems and the grain threshed out using a Wintersteiger single ear thresher (F. Walter - H. Wintersteiger, Austria), modified to allow quantitative collection of threshed grain + chaff. Grain and chaff were separated by passing the grain + chaff fraction over a grain cleaner (A/S Rationale Kornservice sample cleaner) fitted with 3.5 mm top sieve and 2 mm bottom sieve. Straw and chaff were then recombined and N content determined by the Kjeldahl method as above. Carbon content was estimated from organic matter content as determined by the loss on ignition method (MAFF, 1986).

Grain Yield

The plots were combine harvested on 19 August 1992 using a plot combine and yield adjusted to 85% dry matter.

Grain Nitrogen

The combine sample was passed through a riffler divider to obtain a representative 500 g sub-sample. The sample was cleaned using a grain cleaner as above, and after milling through a Hagberg hammer mill, grain protein was measured by near infrared reflectance using an Oxford QN1000 NIR Analyser. Grain N was then estimated from grain protein (grain protein @ 86% DM /5.014).

Soil Water Nitrate Concentrations in the Subsequent Winter

Following harvest, straw was chopped and spread prior to incorporation. After drilling the following wheat crop, the plots were recovered by triangulation and porous ceramic cup soil solution samplers (Richard Earl Ltd., Silsoe, Beds.) installed to a depth of 90 cm as described by Webster *et al.* (1993) (Plate 3 and 4). Five cups were installed per plot, installation was completed by 17 October 1992. From visual inspection of the soil profile to depth at installation, return to field capacity was taken as 12 October 1992. The suction cups were sampled on nine occasions over winter from the time of installation to the beginning of March at approximately 3 week intervals. A hand held 100 ml syringe was used to apply suction (approx. 10 kPa) and collect samples (Plate 5). Cups were left evacuated for approximately two hours before collecting the sample.

Soil solutions were analysed for nitrate by suppressed ion exchange chromatography, using a Dionex QIC-2 ion chromatograph fitted with an AS4A-SC anion exchange solvent compatible column. The quantity of nitrate leached for each plot was calculated from the mean soil water nitrate concentration (mean concentration of 5 cups) on each sample date and cumulative drainage between sample dates as given by MORECS data for the site (Thompson *et al.*, 1981). Mean nitrate concentration in the drainage water over winter was calculated by dividing total quantity of nitrate leached by cumulative over winter drainage.

Soil Mineral N

Soil samples were taken using a set of semi cylindrical gouge augers in the autumn, on the 17 October 1992 after drilling the following crop and in the following spring, on 6 March 1993 prior to the early nitrogen application. The soil was sampled over four depths; 0-15 cm, 15-30 cm, 30-60 cm and 60-90 cm; five cores were taken per plot and the soil from each horizon bulked. Following collection and transport to the laboratory (approx. 4 hours) samples were

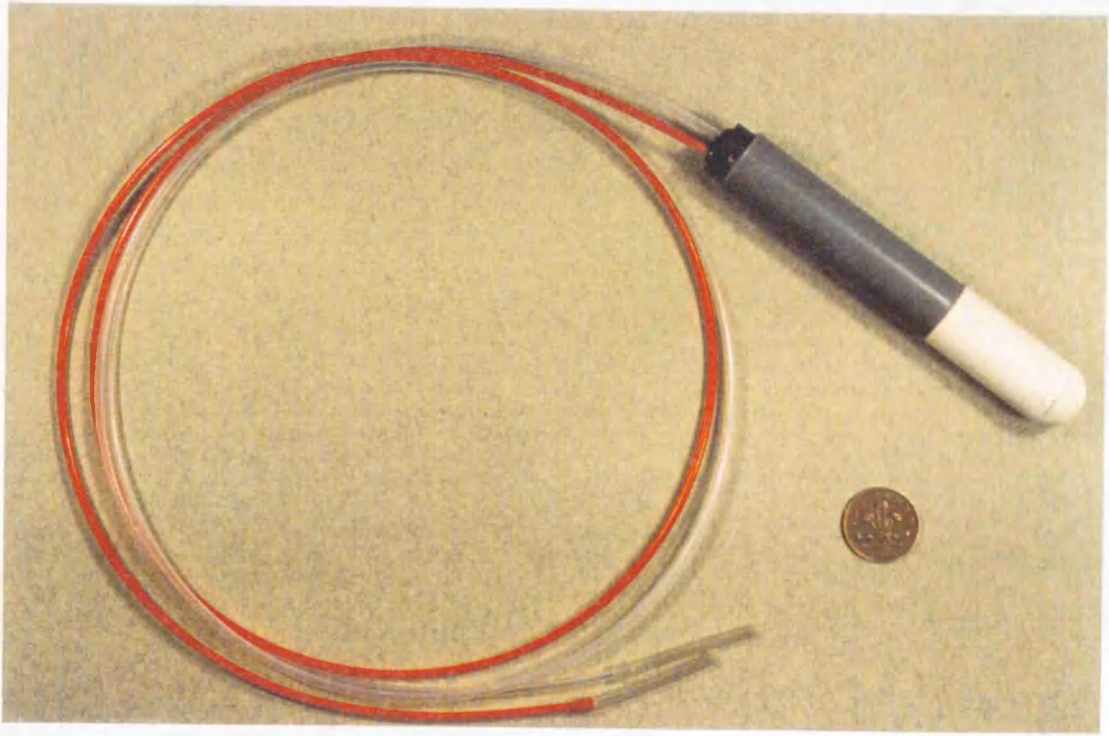


Plate 3

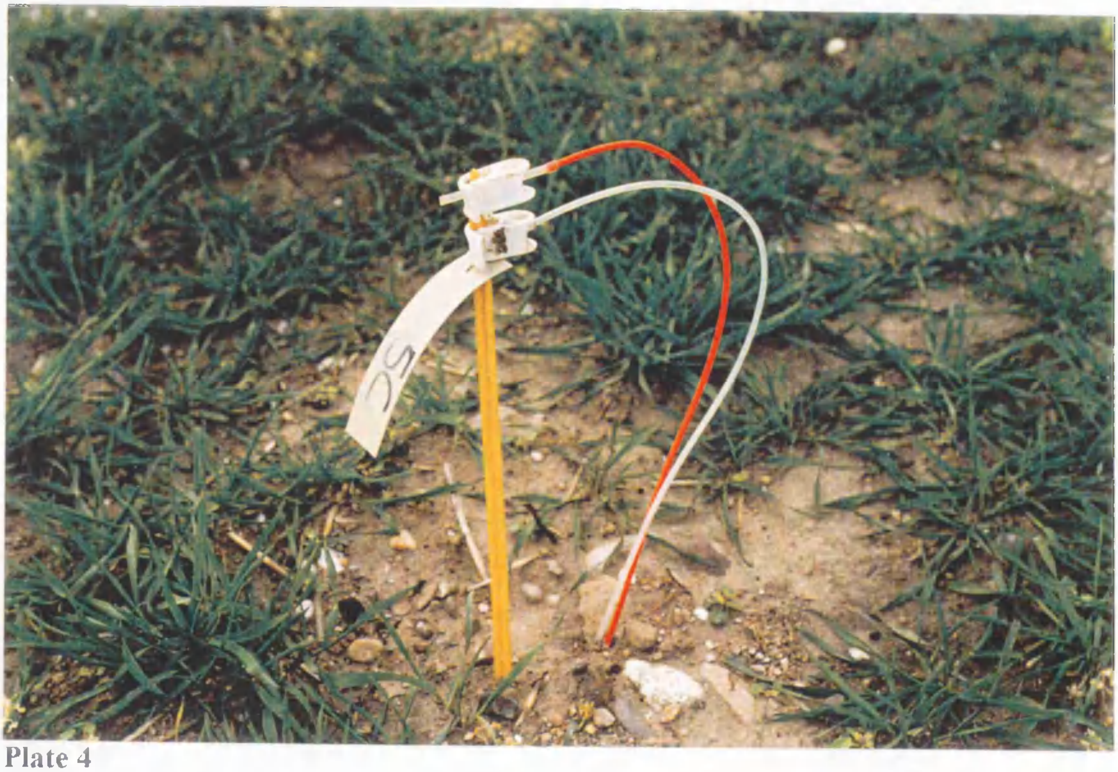


Plate 4

Plates 3 and 4 Ceramic cup soil solution sampler, before and after installation

Plate 5 Sample collection from a ceramic cup

stored frozen prior to analysis. Total soil mineral N (NH_4^+ + NO_3^-) was determined by extracting with KCl followed by steam distillation of the filtered extract with Mg0 and Devardas alloy (Bremner 1965b).

Statistical Methods

Results were analysed using the Genstat 4 statistical programme. The data was analysed by analysis of variance using the method of orthogonal contrasts (Pearce, 1992). Across the urea treatments polynomial contrasts were calculated to examine linear, quadratic, and cubic relationships between the rate of N applied as foliar urea and the variable measured (Ridgman, 1975). For the purposes of the polynomial contrasts, the solid urea treatment was regarded as zero foliar urea. Skeleton analyses of variance were as shown in Table 3.3. All significant results are quoted at the 5% level.

Table 3.3 Skeleton analysis of variance for the main experiment 1992

Source of Variation	Degrees of Freedom		
	Apparent N recovery	Scorch	All other analyses
Blocks	3	3	3
Zero-N v mean of N treatments	-	-	1
Ammonium nitrate v mean of urea treatments	1	-	1
Linear foliar urea	1	1	1
Quadratic foliar urea	1	1	1
Cubic foliar urea	1	1	1
Quartic foliar urea	1	-	1
Deviations	1	-	1
Residual	18	9	21
Total	27	15	31

3.1.3 Results

Weather

Figures 3.2 and 3.3 show higher than average temperatures and rainfall during the spring, July and August were noticeable as particularly wet months. Particularly heavy rainfall events occurred following application of N in the spring. Daily rainfall for this period is shown in Figure 3.4.

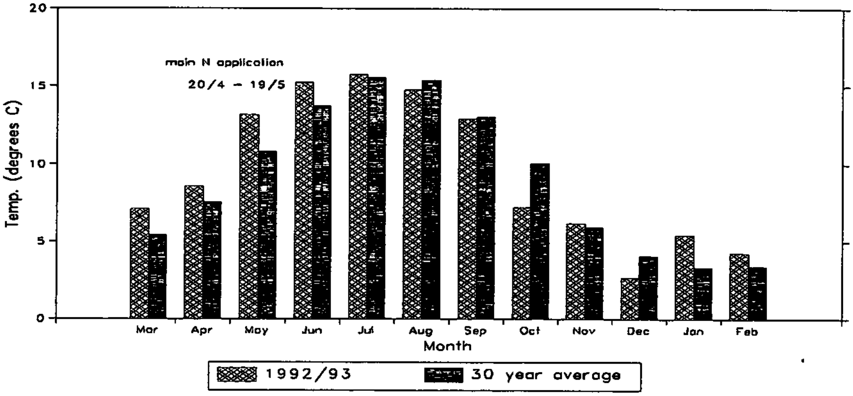


Figure 3.2 Comparison between mean monthly temperatures March 1992 to February 1993 and the 30 year mean (1961-1990)

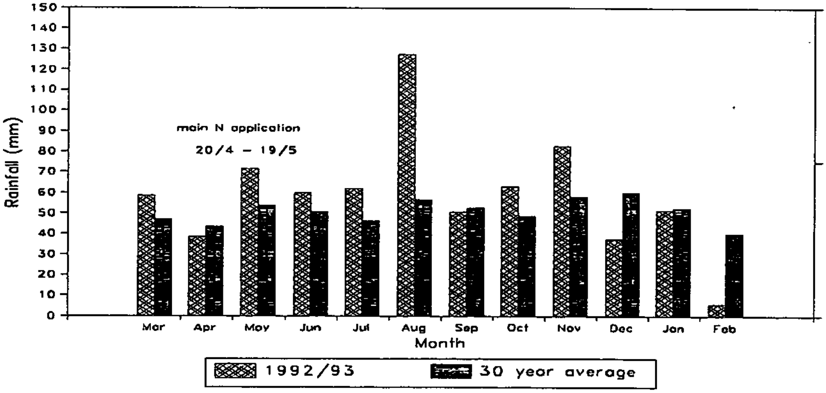


Figure 3.3 Comparison between mean monthly rainfall March 1992 to February 1993 and the 30 year mean (1961-1990)

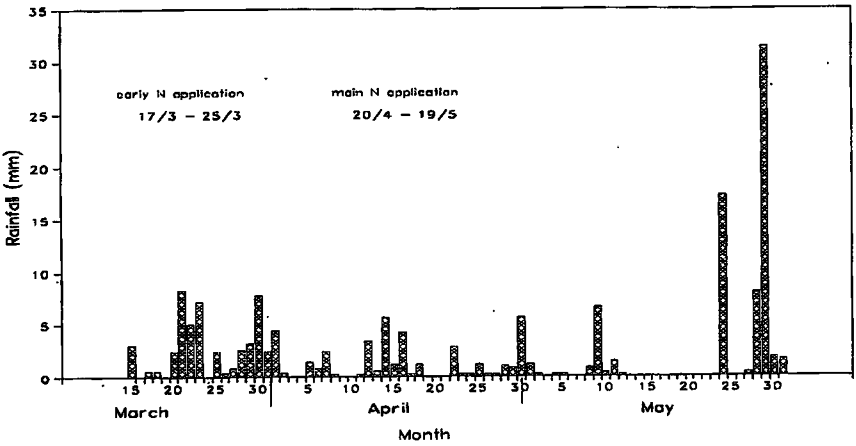


Figure 3.4 Daily rainfall following N application in the spring 1992

<u>Grain Yield</u>

A response to N was recorded; on average N significantly increased grain yield by 3.77 t/ha compared to the zero N treatment (Table 3.4). Mean yield for the urea treatments (7.45 t/ha) was significantly higher than yield obtained with ammonium nitrate (6.27 t/ha). Within the foliar urea treatments yield differences were not significant.

<u>Above Ground Dry Matter Production</u>

On average, N significantly increased above ground dry matter production compared to the zero N treatment (Table 3.4). Above ground dry matter production was not significantly different between the ammonium nitrate treatment (12.19 t/ha) and the mean of the urea treatments (13.0 t/ha). Within the urea treatments, above ground dry matter production decreased significantly with increasing rate of N applied as foliar urea.

Harvest Index (Table 3.4)

There was no significant difference in harvest index between N treatment on average and the zero N plots; neither was harvest index significantly different between ammonium nitrate (0.52) and the urea treatments on average (0.58). Within the urea treatments as the rate of N applied as of foliar urea increased there was an indication that harvest index increased; however, this trend was not significant.

Table 3.4 Grain yield, above ground dry matter production and harvest index in the main experiment 1992

Treatment	Grain yield (t/ha)	Above ground dry matter (t/ha)	Harvest index
Zero N	3.51	7.60	0.477
Ammonium nitrate	6.27	12.19	0.523
Solid urea	7.05	13.81	0.511
30 kg N/ha foliar urea	7.77	14.33	0.540
60 kg N/ha foliar urea	7.30	12.71	0.584
90 kg N/ha foliar urea	7.64	13.38	0.592
120 kg N/ha foliar urea	7.66	12.56	0.624
170 kg N/ha foliar urea	7.25	11.23	0.650
S.E.M.	0.448	0.831	0.0581
C.V. (%)	13.2	13.6	20.60

Scorch

Percentage scorch, as recorded for four of the foliar urea treatments, was low, less than 5% in all cases (Table 3.5). Scorch increased significantly as the rate of N applied as foliar urea increased from 60 kg/ha to 120 kg/ha. At 170 kg N/ha as foliar urea, percentage scorch declined and was not significantly different to that recorded for 90 kg N/ha as foliar urea.

Table 3.5 Scorch (%) for 60-170 kg N/ha applied as foliar urea in the main experiment 1992

Treatment	% Scorch
60 kg N/ha foliar urea	0.14
90 kg N/ha foliar urea	3.04
120 kg N/ha foliar urea	4.96
170 kg N/ha foliar urea	2.41
S.E.M.	0.464
C.V. (%)	35.2

Total Above Ground Nitrogen (kg/ha in the dry matter) and N Content (%N) (Table 3.6)

Nitrogen treatment on average significantly increased nitrogen in the above ground parts of the plant compared to the zero N treatment. Above ground nitrogen was not significantly different between ammonium nitrate and the mean of the urea treatments. Within the urea treatments, above ground nitrogen declined steadily up to 120 kg N/ha as foliar urea but then decreased sharply for 170 kg N/ha as foliar urea. This trend was significant.

Above ground N reflects above ground dry matter production and N content (%N). The trend in above ground N mirrors that of above ground dry matter production, suggesting little difference in N content. N content was not significantly different for the ammonium nitrate treatment and the urea treatments on average. Within the urea treatments, differences in N content of the above ground dry matter were small up to 120 kg N/ha as foliar urea. N content then decreased significantly for 170 kg N/ha as foliar urea.

Grain N Concentration (Table 3.6)

N application significantly increased grain N concentration on average. Grain N concentration for the ammonium nitrate treatment was significantly higher than that for the mean of the urea treatments. Within the urea treatments, differences in grain N concentration were small up to 120 kg N/ha as foliar urea. Grain N concentration then decreased significantly for 170 kg N/ha applied as foliar urea.

Apparent Nitrogen Recovery

Apparent N recovery was 73% for ammonium nitrate and averaged 77% for the urea treatments (Table 3.6); although this difference was not significant. Within the foliar urea treatments, apparent N recovery decreased as the rate of N applied as foliar urea increased up to 120 kg N/ha. The decrease was then more marked for 170 kg N/ha applied as foliar urea. This quadratic trend was significant.

Table 3.6 Above ground N and apparent N recovery in the main experiment 1992

Treatment	Above ground plant N		Grain N (%)	Above ground apparent N recovery (%)
	(%)	kg N/ha		
Zero N	0.988	75.1	1.900	-
Ammonium nitrate	1.633	199.6	2.408	73.2
Solid urea	1.633	229.6	2.423	91.0
30 kg N/ha foliar urea	1.644	234.7	2.373	94.0
60 kg N/ha foliar urea	1.655	210.0	2.378	79.4
90 kg N/ha foliar urea	1.647	218.8	2.348	84.4
120 kg N/ha foliar urea	1.624	203.9	2.324	75.7
170 kg N/ha foliar urea	1.230	138.5	2.054	37.3
S.E.M.	0.0388	14.24	0.0233	8.86
C.V. (%)	5.1	15.1	2.0	23.2

Soil Mineral N (Table 3.7)

In the autumn, nitrogen treatment on average raised total soil mineral N to 90 cm by 17.8 kg/ha. This increase was significant.

Total mineral N to 90 cm was not significantly different between ammonium nitrate and the urea treatments on average. Soil mineral N in the 60-90 cm horizon, however, was significantly higher for the ammonium nitrate treatment than mean of the urea treatments. Soil mineral N in other horizons was not significantly different and compensated for the difference in the 60-90 cm horizon in the total mineral N to 90 cm.

Within the foliar urea treatments, there was a significant linear decrease in total soil mineral N to 90 cm as the rate of N applied as foliar urea increased. The 120 kg N/ha treatment appeared to deviate from this, though this was not significant. The linear decrease in total soil mineral N to 90 cm over the urea treatments was due to a significant decrease in soil mineral N in the 60-90 cm horizon as the rate of N applied as foliar urea increased. Soil mineral N in other horizons was not significantly different.

In the following spring, there was no significant difference in total mineral N to 90 cm between the zero N plots and the N treated plots on average.

Total soil mineral N to 90 cm was significantly higher for the ammonium nitrate treatment than for the urea treatments on average. This was due to significantly higher mineral N in the 60-90 cm horizon; mineral N in other horizons was not significantly different.

Within the foliar urea treatments, total soil mineral N to 90 cm was not significantly different. Differences in mineral N in the 30-60 cm horizon with increasing N applied as foliar urea were significant. However, differences in other horizons were not significant and mineral N in these horizons compensated for differences in the 30-60 cm horizon in the total mineral N to 90 cm.

Table 3.7 Soil mineral N to 90 cm in the main experiment in autumn 1992 and spring 1993

Treatment	Soil mineral N (kg/ha)									
	Autumn					Spring				
	0-15 cm	15-30 cm	30-60 cm	60-90 cm	total	0-15 cm	15-30 cm	30-60 cm	60-90 cm	total
Zero N	22.2	19.2	7.3	7.3	56.0	14.7	15.2	8.3	9.2	49.4
Ammonium nitrate	21.8	20.0	15.6	21.5	78.9	14.6	18.0	9.8	12.8	55.3
Solid urea	22.4	28.3	13.1	19.6	83.4	13.5	15.6	7.0	8.5	44.6
30 kg N/ha foliar urea	23.4	23.6	12.2	15.0	74.2	13.6	12.9	6.6	8.7	43.9
60 kg N/ha foliar urea	19.4	19.7	15.3	17.5	71.8	12.2	13.7	9.0	9.2	44.1
90 kg N/ha foliar urea	19.7	24.1	14.2	12.0	70.0	13.2	15.9	11.0	8.6	49.5
120 kg N/ha foliar urea	21.8	24.5	14.2	18.0	78.6	14.5	16.1	4.4	7.1	44.9
170 kg N/ha foliar urea	19.9	21.9	9.5	8.3	59.5	12.2	10.9	5.6	8.0	42.7
S.E.M.	1.41	3.98	1.95	2.61	5.78	1.29	2.47	1.24	1.24	3.78
C.V. (%)	13.2	35.1	30.7	35.1	16.2	19.0	33.3	32.2	27.5	16.0

Apparent recovery of fertiliser N in the above ground crop has already been presented. Similarly, using the autumn soil mineral N data, apparent recovery of fertiliser N in the soil mineral N fraction can be calculated:

Apparent recovery in soil min. N fraction (%) =

$$\frac{\text{Soil min. N (kg/ha) - Soil min. N in zero N plot (kg/ha)}}{\text{Fertiliser N applied (kg/ha)}}$$

The sum of the apparent fertiliser N in the above ground crop and in the soil mineral N fraction in the autumn permits a crude apparent N balance to be calculated for the plant-soil mineral N system (Table 3.8).

Table 3.8 Apparent N balance for the main experiment 1992

Treatment	Apparent recovery (%)			Loss / gain (%)
	Above ground crop	Autumn soil mineral N (0-90 cm)	Total	
Ammonium nitrate	73.2	13.5	86.7	-13.3
Solid urea	91.0	16.1	107.1	+7.1
30 kg N/ha foliar urea	94.0	10.7	104.7	+4.7
60 kg N/ha foliar urea	79.4	9.3	88.7	-11.3
90 kg N/ha foliar urea	84.4	8.2	92.6	-7.4
120 kg N/ha foliar urea	75.7	13.3	89.0	-11.0
170 kg N/ha foliar urea	37.3	2.0	39.3	-60.7

C/N Ratio of Incorporated Straw (including chaff)

The C/N ratio of the straw + chaff fraction left on the field at harvest and incorporated into the soil in the autumn are given in Table 3.9.

As expected, N application on average significantly decreased the C/N ratio of plant material. Plant material from the urea treatments, on average, had a significantly higher C/N ratio than the ammonium nitrate treatment. Within the urea treatments, the C/N ratio decreased slightly up to 60 kg N/ha as foliar urea and then increased from 90 to 120 kg N/ha as foliar urea and almost doubled from 120 to 170 kg N/ha as foliar urea. This cubic trend was significant.

Carbon content (%C) was similar for all treatments. The significant difference in C/N ratio between the ammonium nitrate treatment and the mean of the urea treatments, and the significant cubic trend across the urea treatments, to a large extent reflects the lower apparent N recovery in the above ground crop and N content for the all foliar urea treatment.

Table 3.9 C/N ratio of straw and chaff fraction returned to soil in the main experiment 1992

Treatment	C/N ratio of straw + chaff
Zero N	140.9
Ammonium nitrate	58.0
Solid urea	61.0
30 kg N/ha foliar urea	58.6
60 kg N/ha foliar urea	56.5
90 kg N/ha foliar urea	59.5
120 kg N/ha foliar urea	63.4
170 kg N/ha foliar urea	113.1
S.E.M.	4.14
C.V. (%)	10.8

<u>Soil Water Nitrate Concentration and Estimated Leaching Losses</u> (Table 3.10, Figure 3.5)

Figure 3.5 shows the variation in soil water nitrate concentration for each treatment over the nine sampling dates. Peak nitrate concentrations occurred for all N treatments early on in the drainage period, within two weeks of each other, except for 170 kg N/ha applied as foliar urea. Peak concentration for the all foliar urea treatment occurred noticeably later, just before drainage ceased, on the 14 January 1993.

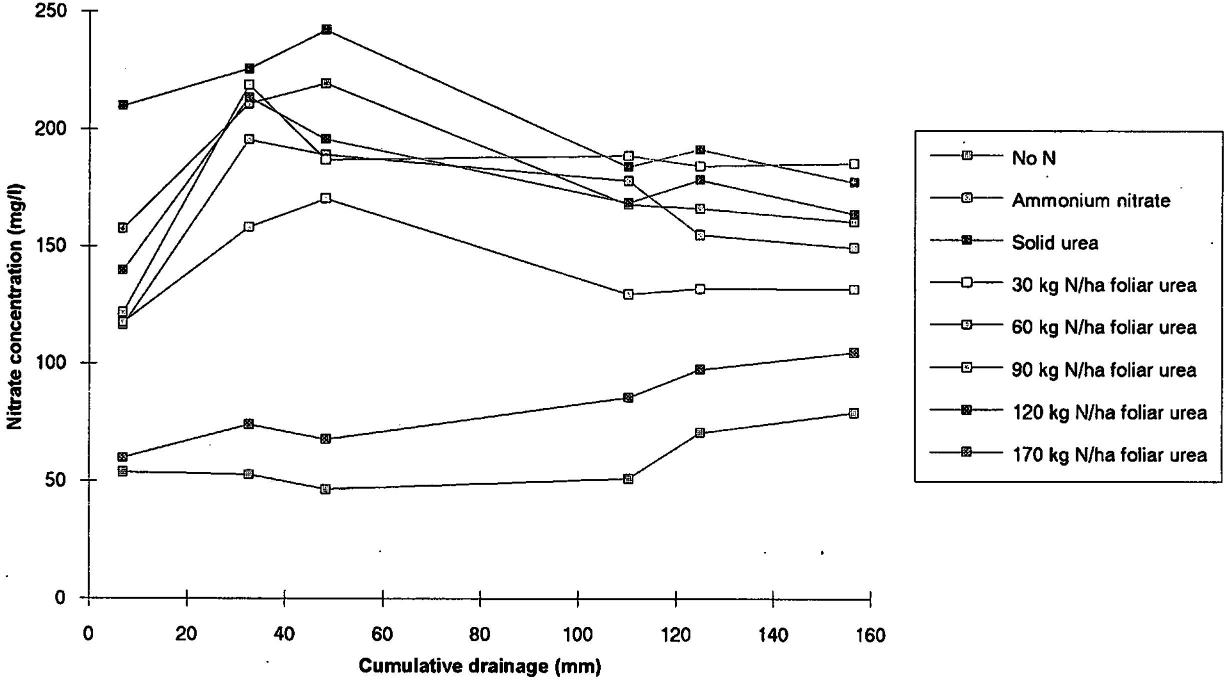


Figure 3.5 Soil water nitrate concentrations over winter 1992/93 for 170 kg N/ha applied as ammonium nitrate and as different proportions of foliar urea in the main experiment

Nitrogen treatment, on average , significantly increased mean soil water nitrate concentration (165.9 mg/l v 56.5 mg/l) and estimated nitrate-N leaching losses (59 kg/ha v 20.0 kg/ha) compared to the zero N treatment.

Average nitrate concentration and estimated quantity of nitrate-N leached over the drainage period was 171.9 mg/l and 61 kg/ha respectively for the ammonium nitrate treatment and 164.9 mg/l and 58 kg/ha respectively for the urea treatments on average; these differences were not significant. While differences in nitrate concentration and quantity of nitrate-N leached were not significant between ammonium nitrate and the urea treatments on average, Tukeys test (Sokal & Rohlf, 1981) showed that 170 kg N/ha as foliar urea, significantly reduced average soil water nitrate concentration and nitrate-N leached compared to ammonium nitrate.

Within the foliar urea treatments, there was a significant linear decrease in average soil water nitrate concentration and leaching losses over the drainage period as the rate of N applied as foliar urea increased. The 120 kg N/ha foliar urea treatment appeared to deviate from this, though this was not significant.

Table 3.10 Mean soil water nitrate concentration and nitrate-N leached in the drainage water over winter 1992/93 in the main experiment

Treatment	Mean nitrate concentration in soil water (mg/l)	Nitrate-N leached (kg/ha)
Zero N	56.5	20.0
Ammonium nitrate	171.9	60.8
Solid urea	209.2	74.0
30 kg N/ha foliar urea	185.7	65.7
60 kg N/ha foliar urea	187.4	66.3
90 kg N/ha foliar urea	145.9	51.6
120 kg N/ha foliar urea	180.5	63.9
170 kg N/ha foliar urea	80.6	28.5
S.E.M.	17.88	6.33
C.V. (%)	23.5	23.5

3.1.4 Discussion

Yield, Above Ground Dry Matter and Harvest Index

Average wheat yield for the West Midlands was 6.61 t/ha for the 1992 harvest (MAFF, 1992). Mean yield for the nitrogen treatments, was therefore above average.

In this experiment application of N as urea, on average, significantly increased grain yield compared to ammonium nitrate, there was, however, no significant difference between urea treatments. The effect of N source is confounded by the effect of time of application, since in those treatments receiving N as foliar urea, the crop not only received a different source of N, but also received N at a different time. However, yield for the solid urea treatment that received N at the same time as the ammonium nitrate treatment was significantly higher than for the ammonium nitrate treatment, but not significantly different to that for the foliar urea treatments. This suggests, that the increase in yield for the urea treatments on average, is due to source of N (urea c.f. ammonium nitrate) rather than timing. This is in contrast to other work, where the yield response to N as urea has usually been reported as inferior compared to ammonium nitrate (Van Burg, 1986; Chaney and Paulson, 1988). The inferior response for N applied as ammonium nitrate may have been related to rainfall following application, causing rapid leaching of the more mobile NO_3^- ion beyond the rooting zone. Reference to weather data (Figure 3.4) shows that 24 mm of rain fell in the 7 days following application of the early 50 kg N/ha in March and particularly heavy rain fall events occurred in late May (17.2 mm and 31.4 mm of rain fell on the 24/5 & 30/5 respectively), when it is likely that an appreciable amount of the main 120 kg N/ha, applied on the 20/4, would have still remained in the soil to be taken up.

Most references in the literature to application of N as foliar urea refer to late applications, in addition to the main N application to the soil in the spring, to influence grain protein. Very little work is reported where foliar urea has been used to entirely replace the main N application in the spring. In contrast to the results of this experiment, Poulton *et. al* (1990) reported a significant decrease in grain yield as a result of applying 160 kg/ha of the main spring N application as foliar urea compared to soil applied urea ammonium nitrate (UAN). Severe scorch, exacerbated by the use of a wetting agent, was implicated. In this experiment while scorch was observed, it was not severe and less than 5% in all treatments assessed. This low level of scorch may account for the lack of any yield reduction from application of N as foliar urea. In agreement with the findings here, Kettlewell and Juggins (1992) have reported no significant effect on yield for 125 kg N/ha applied as foliar urea sprays between GS 32 and 37 and Warden and Kettlewell (1993) recorded no effect on yield for up to 210 kg N/ha applied as foliar urea all at GS 32. Levels of scorch were relatively low in both of these studies.

In the experiment of Poulton *et al.* (1990), the reduction in grain yield for N applied as foliar urea compared to soil applied N was associated with a significant decrease in total above ground dry matter production (grain + straw). Harvest index, the proportion of total above ground dry matter in the grain, was the same for both treatments. In this experiment, total above ground dry matter was not significantly different for the ammonium nitrate treatment and the mean of the urea treatments. Harvest index, however, was higher for the urea treatments on average than for the ammonium nitrate treatment, although this difference was not significant. Within the urea treatments, total above ground dry matter production decreased significantly as the rate of N applied as foliar urea increased. There was a corresponding increase in harvest index, although again this was not significant.

The significant increase in grain yield, with no significant difference in above ground dry matter production for the urea treatments on average compared to ammonium nitrate; and within the urea treatments, the significant reduction in above ground dry matter production with no significant effect on grain yield as the rate of N applied as foliar urea increased, would suggest a significant increase in harvest index with increasing rate of N applied as foliar urea. The lack of any significant trend for the harvest index values, as shown by the statistical analysis, is due to the greater variability of the harvest index data (c.v. 21%) compared to its component parts (c.v. yield 13.2%, c.v. above ground dry matter 13.6%). Therefore, despite the lack of significance, the results suggest that the effects of foliar urea on grain yield are due to increased partitioning of above ground dry matter to the grain.

Although yield of straw was not measured directly, indirect observations can be drawn from the above ground dry matter and harvest index data. Above ground dry matter production was not significantly different for the ammonium nitrate treatment and the urea treatments on average, therefore, given the higher harvest index for the urea treatments on average, ammonium nitrate must have increased straw (+ chaff) yield. Similarly, within the urea treatments, the significant overall decrease in above ground dry matter production with an increase in harvest index, suggests a decrease in straw (+ chaff) production with increasing amount of N applied as foliar urea. Poulton *et al.* (1990) also reported lower yields of straw for N applied as foliar urea. Juggins (1991), however, reported a higher straw yield on average, for foliar applied urea than for soil applied ammonium nitrate, despite no grain yield response to N.

Increased harvest index and reduced straw production with increasing rate of N applied as foliar urea may be due to timing of application. An increasing proportion of total N is applied later as the rate of N applied as foliar urea increases. A smaller proportion of later applied N is used for synthesis of structural materials in the non grain parts of the plant compared to earlier applied N. Later applied N is therefore more likely to be translocated to the grain and less likely to influence straw yield (Dilz, 1964).

Scorch

Degree of scorch as recorded for four of the foliar urea treatments was very low, in all cases less than 5%. Juggins (1991) reported similar low levels of scorch for 125 kg N/ha applied as foliar urea over a similar time scale. Warden and Kettlewell (1993) recorded 7-12% scorch for 60-170 kg N/ha as foliar urea, although the foliar urea was applied over a much shorter time scale. Poulton *et al.* (1990) reported severe scorching but attributed this to the use of a wetting agent. Finck (1982) has suggested that rapid drying of the urea solution on the leaves reduces the risk of scorch, while glasshouse studies (Peltonen *et al.*, 1991) and field experiments (Gooding, 1988) have suggested that urea causes most scorch if it remains in solution on the leaf tissue for an extended period of time. The dry, warm weather conditions at application may thus have contributed to the low levels of scorch recorded in this experiment.

The results show scorch increasing as the rate of N applied as foliar urea increases, up to 120 kg N/ha as foliar urea, and then decreasing for 170 kg N/ha as foliar urea. Scorch was only assessed on one occasion, however, three days after the final application of foliar urea. At the time of scorch assessment therefore, of the treatments assessed (60, 90, 120 and 170 kg N/ha as foliar urea), as the rate of N applied as foliar urea increased the time interval between the last application of foliar urea and assessment was reduced. The increase in scorch from 60 to 120 kg N/ha as foliar urea may therefore be due to reduced recovery of green tissue following application, due to reduced time between final application and assessment. The significantly lower scorch recorded for 170 kg N/ha as foliar urea treatment than for the 120 kg N/ha foliar urea treatment is inconsistent. Both treatments received their final application of foliar urea on the same date.

Significant differences in scorch between foliar urea treatments were not reflected in yield differences between these treatments. Similar findings have been reported by other workers: Juggins (1991) and Warden and Kettlewell (1993) reported no significant effect on yield for early applications of foliar urea (GS 32 to 37), and Dampney and Salmon (1990) have reported no significant effect on yield for levels of scorch less than 10% due to foliar urea applied over a range of later timings (GS 39 to 90). The lack of any effect on yield of low levels of scorch, may be due to compensation by plants for small amounts of scorch damage: Ledent (1984) has reported no significant effect on yield due to partial defoliation and Turly and Ching (1986) working on seedling leaves, have reported an increase in green leaf area and chlorophyll content as a result of foliar applications of urea ammonium nitrate.

Apparent N Recovery

The apparent N recovery recorded in this experiment, is high compared to other data. Bock (1984) refers to the commonly cited figure of 50-60% for apparent N recovery of soil applied N in the crop. Bloom *et al.* (1988) have reported a range in apparent N recovery from 43 to 88% for soil applied N. ^{15}N work has indicated true crop recovery in the range 39 to 87% for soil applied N in the spring (Powlson *et al.*, 1992; Powlson *et al.*, 1986a and McDonald *et al.*, 1989); corresponding apparent N recovery can be calculated to range from 30 to 100%. Little information in the literature is available regarding recovery of early foliar applications of N; Poulton *et al.* (1990) reported true recovery in the crop of 48-54% according to time of application using ^{15}N. In trials involving foliar applications of ^{15}N labelled urea around anthesis, recovery of 45-77% has been reported (Powlson *et al.*, 1987a; Powlson *et al.*, 1989a). Corresponding apparent N recovery was not reported in these studies and lack of data for zero N control plots precludes its calculation.

Poulton *et al.* (1990) reported foliar applied nitrogen to be recovered (true recovery) by the crop as efficiently as soil applied N. In contrast in this experiment, apparent N recovery within the urea treatments, show N to be recovered less efficiently by the crop as the rate of N applied as foliar urea increases. This decrease in apparent N recovery in the crop was not reflected in an increase in soil mineral N in the autumn. In fact the converse occurred, total soil mineral N to 90 cm decreased significantly as the rate of N applied as foliar urea increased. Gaseous losses and / or immobilisation of fertiliser N are therefore indicated, and the data suggests that these can be substantial at high rates of N applied as foliar urea. As no measurements were made to quantify either of these pathways, a direct estimate of the importance of gaseous losses in this experiment is not possible. Ammonia volatilisation increases with temperature and wind speed and denitrification increases with temperature (Haynes and Sherlock, 1986). Application of foliar urea early in the day, followed by warm windy conditions, would therefore have been likely to be conducive to gaseous losses of N by volatilisation and / or denitrification, following hydrolysis of urea to NH_4^+. Alternatively, the significant increase in the C/N ratio of the straw + chaff fraction as the rate of N applied as foliar urea increased, would have favoured an increase in fertiliser N removed from the plant-soil mineral N system by immobilisation in the autumn, following ploughing. Due to the short time interval between ploughing and soil sampling, however, this effect is likely to have been limited.

The simple N balance (apparent) presented in Table 3.8 shows an estimated total apparent N loss from the plant-soil mineral N system of 60% for 170 kg N/ha applied as foliar urea. Poulton *et al.* (1990) estimated true losses of 30-40% from the crop - soil system for 120 kg N/ha as foliar urea.

The significant decrease in apparent N recovery for the 170 kg N/ha foliar urea treatment is notable. This treatment received 120 kg N/ha as urea sprays at the same time as the 120 kg N/ha foliar urea treatment. The implication, is that the reduced apparent N recovery for the all foliar urea treatment is attributable to N losses associated with the early 50 kg N/ha applied as foliar urea around GS 21. Following application of the early N, plots receiving 170 kg N/ha as foliar urea appeared N deficient, the crop was shorter and thinner than other plots receiving the early 50 kg N/ha as solid N. Further, poor crop growth following the early application of N for this treatment may have exacerbated losses from subsequent N applications.

The decrease in apparent N recovery in the crop and in the soil mineral N fraction with increasing rate of N applied as foliar urea, could be a reflection of form of nitrogen application (i.e. solid vs foliar) or time of application. As the rate of N applied as foliar urea increases, a larger proportion is potentially supplied via the foliage than the soil and an increasing proportion of the total N is applied later. The latter is likely to be important in terms of crop cover at the time of application and therefore percentage interception.

No assessment of crop cover at application was made in this experiment, however, it may be expected that due to the larger proportion of N applied later as the rate of N applied as foliar urea increases, crop cover and thus percentage interception would have been higher. N as urea falling on the soil surface would have been subject to immobilisation or losses by volatilisation and, after conversion to nitrate, denitrification. The most likely cause of loss of N for urea falling on the foliage would have been volatilisation as the urea was hydrolysed (Powlson *et al.*, 1987a; Poulton *et al.*, 1990). If it is assumed that the amount of urea intercepted by the leaves increased as the rate of N applied as foliar urea increased, due to increased crop cover as a result of a larger proportion of N applied later, then it is logical to speculate that any unaccounted for N due to gaseous losses is a result of volatilisation rather than denitrification. Poulton *et al.* (1990) tentatively implicated volatilisation as important in contributing to the higher overall unaccounted for N for early application as foliar urea compared to soil applied UAN mixture. Volatilisation has also been attributed as the principle cause of loss of late application of foliar urea (Powlson *et al.*, 1989a; Powlson *et al.*, 1987a).

The significant decrease in apparent N recovery within the urea treatments, with no corresponding decrease in yield, indicates an increase in physiological N use efficiency as the proportion of N applied as foliar urea increases. This increase in physiological efficiency, reflects the increase in harvest index as the rate of N applied as foliar urea increases.

N treatment, as expected, significantly increased N concentration in the grain. Grain N concentrations for all N treatments were generally high. The lower concentration of N in the grain for foliar applied N compared to soil applied N as found in this experiment, has also been reported by Poulton *et al.* (1990). These findings, however, are in contrast to those reported for late applications of foliar urea, where an increase in grain N concentration is usually recorded (Powlson *et al.*, 1989a).

Soil Mineral N

Numerous references in the literature can be found to soil mineral N concentrations following winter wheat for land in continuous cereals or in arable rotations: MacDonald *et al.* (1989) reported 15 kg N/ha to 60 cm following applications of 136 kg N/ha, Addiscott and Powlson (1989) reported 48 kg N/ha in the top 1 m following 192 kg N/ha and Chaney (1990) recorded an average of 60 kg N/ha to 90 cm for eight sites. These figures are less than the mean soil mineral nitrogen to 90 cm as recorded in this experiment (74 kg N/ha mean soil mineral N all N treatments). The latter references, however, refer to soil mineral nitrogen immediately after harvest, before mineralisation of N in the autumn. Soil samples in this experiment were taken in late autumn (17 October) after drilling the following crop. The mild wet conditions (Figure 3.2 and 3.3) would have favoured mineralisation. Addiscott and Powlson (1992) quote a general figure of 30 kg N/ha for mineralisation in the autumn. References to soil mineral N to 90 cm as measured in the autumn, i.e. including the contribution from mineralisation, range from 30 to 155 kg N/ha (Jenkinson, 1986; Goulding & Webster, 1992; Harris & Rose, 1992; Harrison, 1995). Allowing for the contribution of mineralisation, autumn soil mineral N figures as recorded in this experiment, are therefore in the range reported by others.

Considering distribution of N in the profile, the top soil (0-30 cm) contained more nitrate than each of the lower horizons. The mean results for all N treatments show the relative proportions were; 60% in the top soil, 18% in the 30-60 cm and 21% in the 60-90 cm horizon. Chaney (1990), for 160 kg N/ha applied, found on average; 50% of the residual nitrate in the 0-30 cm horizon, 30% in the 30-60 cm horizon and 20% in the 60-90 cm horizon. A continual decrease throughout the profile, rather than approximately equal proportions in the lower horizons as recorded here. The significantly higher proportion of soil mineral N in the 60-90 cm horizon for ammonium nitrate compared to the urea treatments on average, may be attributable to the initial rapid leaching of the more mobile NO_3^- ion (c.f. less mobile NH_4^+ ion for the urea treatments) following particularly heavy rainfall events after application in the spring (Figure 3.4).

MacDonald *et al.* (1989) reviewing data from a number of experiments, have shown that of the fertiliser N applied in the spring, on average only 1-2% is present in mineral forms in the soil at harvest. Differences in soil mineral N in the autumn are therefore unlikely to be related to differences in fertiliser N remaining in soil and more likely to reflect differences in the mineralisation / immobilisation balance of native soil mineral N. The high C/N ratio of the straw + chaff for the zero N treatment and the all foliar urea treatment would have been conducive to immobilisation of soil mineral N in the organic fraction. This hypothesis is some what tenuous given the very short time interval between straw incorporation and soil sampling, however, the C/N ratio of the incorporated straw + chaff for these treatments was at least twice that of other treatments.

The 46 kg N/ha (mean of all N treatments) soil mineral N to 90 cm as recorded in the spring, agrees reasonably well with the soil mineral N value of less than 40 kg/ha expected for sandy soils following cereals according to the ADAS classification for soil mineral N supply in arable rotations (Chambers, 1992a). The significantly higher soil mineral N in the spring for the ammonium nitrate compared to the urea treatments on average, is unexpected given the lack of any difference in the autumn; it is not clear why this has occurred.

Differences in soil mineral N in the autumn and spring, cannot be related to N losses by leaching as estimated from the ceramic cup data. Difference in soil mineral N in autumn and spring, reflects the balance between; N losses from the soil system through crop uptake, N leaching, immobilisation and denitrification, and N inputs from atmospheric deposition and mineralisation. That the difference in autumn and spring soil mineral N indicates a lower net N loss from the soil than that measured as leached in the soil water, may be attributed to inputs from the atmosphere and / or mineralisation. It is likely that the mild wet autumn would have been conducive to the latter.

Nitrate Leaching

Soil mineral N in the autumn indicates the quantity of mineral-N potentially at risk to leaching during the subsequent winter. Soil mineral N data in the autumn for the treatments as discussed, supports the nitrate-N leaching losses as detected in the ceramic cups i.e. higher leaching losses were recorded for treatments having higher soil mineral N in the autumn. Differences in quantity of N leached between treatments, however, are noticeably larger than differences in soil mineral N in the autumn. Difference in the C/N ratio of incorporated straw + chaff influencing mineralisation / immobilisation balance in the soil was tentatively suggested as a possible factor influencing differences in soil mineral N in the autumn, though it was noted that the very short time interval between straw incorporation and soil sampling was likely to have been limiting. The continued effect of this factor after soil sampling in the autumn could have been expected to further increase differences in soil mineral N, and therefore differences in quantity of N leached between treatments as recorded in the ceramic cups. The mild wet conditions recorded for October, November and January (Figure 3.2 and 3.3) would have been conducive to this. The noticeably later peak in soil water nitrate concentration for the all foliar urea treatment can be related to the smaller proportion of mineral N in the lower horizons for this treatment in the autumn.

For all treatments, concentrations measured and associated nitrate-N leaching losses are particularly high. The nitrate concentration in soil water leaching from the zero-N treatments (56.5 mg/l) exceeds the limit of 50 mg/l of nitrate in potable waters, as set by the EU (Council of European Communities, 1980 & 1991). The all foliar urea treatment is almost double this limit and other N treatments are at least three times the limit.

Mean soil water nitrate concentrations recorded here are also high compared to other reported data. Kettlewell and Juggins (1992), have reported soil water nitrate concentrations of 65-105 mg/l and 50-100 mg/l for 124 kg N/ha applied as ammonium nitrate and as foliar urea respectively. With the exception of the all foliar urea treatment, mean soil water nitrate concentrations reported here are substantially higher than this. Further, Kettlewell and Juggins (1992) results followed a dry growing season when yield and apparent N recovery by the crop were low. As such, the results themselves can be regarded as high.

Addiscott and Powlson (1989) cite figures of 34-59 mg/l of nitrate for application of 0-192 kg N/ha on the Broadbalk field (silty clay loam) at Rothamsted and while nitrate leaching on sandy soils can be expected to be approximately twice that on clay soils (Goulding and Poulton 1992), the soil water nitrate concentrations as recorded in this experiment are considerably higher than this, irrespective of the form or method of application.

According to Goulding and Poulton (1992), average losses of N as nitrate from sandy soils in continuous arable production, are likely to be in the order of 20 kg N/ha per year; a similar figure is given by Davies and Archer (1990). Goulding and Poulton (1992) also highlight the effect of weather by affecting drainage, on N leaching losses. They cite the variation in loss of 10 and 51 kg N/ha per year as nitrate, corresponding to 140 mm and 330 mm of drainage respectively, from a sandy soil under continuous cereals. Lord (1992) has estimated average nitrate leaching from winter cereals in the UK to be about 35 kg N/ha/year at optimum amounts of N applied.

Given the average winter rainfall and cumulative drainage (157 mm) as calculated from MORECS data, the nitrate-N leaching losses recorded in this experiment are therefore high, reflecting the high soil water nitrate concentrations but average drainage. Nitrate-N leaching losses from the zero-N treatment were in the order of that expected for arable sand land, while those recorded for the N treatments were 2 to 3 times this.

Despite the unusually high values of the results in general, they show that mean soil water nitrate concentration and nitrate-N leaching losses decrease as the rate of N applied as foliar urea increases. Further, while mean soil water nitrate concentrations and nitrate-N leaching losses were not significantly different between the ammonium nitrate treatment and the urea treatments on average, application of N all as foliar urea did significantly reduce mean soil water nitrate concentration and nitrate-N leaching losses compared to ammonium nitrate. This agrees with the reduced soil water nitrate concentration for N applied as foliar urea, as reported by Kettlewell and Juggins (1992) and the observation by Poulton *et al.* (1990), that less fertiliser nitrogen was recovered in the soil for N applied as foliar urea.

3.2 MAIN EXPERIMENT 1993

In the main experiment carried out in 1992, a decrease in above ground dry matter production and an increase in harvest index were recorded as the rate of N applied as foliar urea increased. In the second year of the work, basic growth analysis was introduced to investigate further the effect on above ground dry matter production. The objectives of the main experiment in the second year were therefore :

1) To repeat the main experiment using the same plots, to account for seasonality effects.
2) In addition, to monitor shoot populations, green area index and above ground dry matter production during the growing season, to determine the physiological basis of the decrease in above ground dry matter production as the rate of N applied as foliar urea increased, as recorded in year 1.

3.2.1 Field Treatments

The Little Pipe Strine site was redrilled with winter wheat (*Triticum aestivum* cv. Beaver) on 12 October 1992. Seedbed cultivations consisted of straw incorporation by ploughing (to approximately 30 cm) and pressing followed by a Roterra type cultivation. Baytan treated C2 seed was drilled using a combination drill with a row spacing of 12.8 cm. Seedbed fertiliser consisted of 37 kg/ha phosphate (P_2O_5) and 56 kg/ha potash (K_2O).

The experimental site was recovered by triangulation, such that each plot occupied the same position in the field as in year 1 (Figure 3.1). Nitrogen treatments were as in year 1 (Table 3.1), such that each plot received the same N treatment as in year 1. Details of N applications were as given for year 1. Actual dates and growth stages of applications are given in Table 3.11.

Table 3.11 Dates of N applied in the main experiment 1993

					TREATMENT				
ZGS	Date Applied	Zero-N	NH_4NO_3 (kg N/ha)	Solid urea (kg N/ha)	30 kg N/ha Foliar urea	60 kg N/ha Foliar urea	90 kg N/ha Foliar urea	120 kg N/ha Foliar urea	170 kg N/ha Foliar urea
23	16/3		50	50S	50S	50S	50S	50S	30F
23/24	25/3								20F
30/31	19/4		120	120S	90S	60S	30S	-	-
31	22/4				30F	30F	30F	30F	30F
31	27/4					30F	30F	30F	30F
31	2/5						30F	30F	30F
32	7/5							30F	30F
Total		0	170	170	170	170	170	170	170

S = Urea applied as solid   F = Urea applied as foliar spray

3.2.2 Sampling and Analytical Techniques

Scorch

For treatments 4, 5, 6, 7 and 8, leaf scorch was assessed 4 to 5 days after each application of foliar urea. The youngest fully expanded leaf of 20 randomly selected plants per plot was examined and the necrotic area due to scorch scored subjectively using a Septoria disease assessment key (Anon., 1976). Mean values per plot were calculated for statistical analysis.

Shoot Counts

On 6 March 1993, two adjacent 0.5 m lengths of row were marked using white pot labels at four positions per plot in blocks 1, 2 and 3, and the number of plants counted. The marked rows were located along the north and south edges of each plot, four rows in from the edge. The objective being to avoid edge effects but to minimise plot damage when counting shoots, particularly later in the season. The number of live shoots in the marked lengths of row were counted every 7 to 10 days from the beginning of April to mid June. A shoot was classed as dead when the tip of the shoot had died.

Growth Analysis

On 9 May, 12 June and 16 July 1993, a 0.72 m^2 quadrat from each plot in block 1, 2 and 3 was destructively sampled by cutting off all plant material at ground level. Weeds were excluded and all dead material on the ground around the stem base was collected. Samples were stored at 5^0C prior to analysis to reduce leaf roll.

The fresh weight of the bulk sample was recorded and a sub-sample (25% by fresh weight on sample date 1 and 20% by fresh weight on sample date 2 and 3) separated. The sub-sample was separated into live leaf, live stem (leaf sheath + stem) and dead (leaf + dead) on sample date 1 and in addition ear and flag leaf on sample dates 2 and 3. The green area of the live components was determined using a leaf area meter (Delta-T Devices, Cambridge), calibrated using a shape of known area. The leaf sample was further sub-sampled (50% by fresh weight) for this purpose. The dry weight of the sub-sample components was determined by drying at 80 °C for 48 hours.

Above Ground Dry Matter at Harvest

On 19 August, plants were removed at soil level from two adjacent 0.25 m lengths of row at four positions per plot. The samples were bulked and the whole plant material dried at 80 °C for 48 hours. Total above ground dry matter was calculated using row width to determine sampling area.

Above Ground Plant N and C/N Ratio of Incorporated Straw + Chaff

Above ground plant N content and the C/N ratio of the straw and chaff returned to the plots was determined as in year 1. Apparent recovery of fertiliser N in the above ground plant dry matter was calculated for each plot.

Grain Yield

The plots were combine harvested on 27 August 1993 using a plot combine and yield adjusted to 85% dry matter.

Grain Nitrogen

Grain N was estimated from grain protein determined from the combine sample as in year 1.

Soil Water Nitrate Concentrations in the Subsequent Winter

Following harvest, straw was chopped and spread prior to incorporation. The above ground portion of the tubes from the ceramic suction cups were buried at 30 cm along with a magnet. After ploughing to 20 cm and pressing in mid September, the following wheat crop was drilled on 16 October 1993 and the plots recovered by triangulation. The buried tubes were relocated with the aid of a magnet detector, recovered to the surface and the holes backfilled. By visual inspection of the soil profile to depth, the return to field capacity was taken as 4 October. The suction cups were sampled on ten occasions over winter from the time of installation to mid February 1994 at approximately fortnightly intervals, the precise interval between sampling varied according to the amount of rainfall following the previous sample date. Details of sampling and analytical procedures were as for year 1. Nitrate leached was calculated from average soil water nitrate concentration on each sample date and cumulative drainage between sample dates as given by MORECS data for the site (Thompson *et al.*, 1981).

Soil Mineral N

Soil samples were taken using a set of semi cylindrical gouge augers in the autumn, on the 23 October 1993 after drilling the following crop and in the following spring, on 27 February 1994 prior to the early nitrogen application. The soil was sampled over four depths; 0-15 cm, 15-30 cm, 30-60 cm and 60-90 cm; five cores were taken per plot and the soil from each horizon bulked. Analytical procedures were as detailed for year 1.

Statistical Methods

Statistical methods were as detailed for year 1. Skeleton analyses of variance were as shown in Table 3.12. All significant results are quoted at the 5% level.

Table 3.12 Skeleton analysis of variance for the main experiment 1993

Source of Variation	Degrees of Freedom	
	Apparent N recovery	All other analysis
Blocks	3	3
Zero-N v mean of N treatments	-	1
Ammonium nitrate v mean of urea treatments	1	1
Linear foliar urea	1	1
Quadratic foliar urea	1	1
Cubic foliar urea	1	1
Quartic foliar urea	1	1
Deviations	1	1
Residual	18	21
Total	27	31

3.2.3 Results

Weather

Monthly temperatures and rainfall are shown in Figures 3.6 and 3.7. Temperature and rainfall were above average in the spring and summer. The autumn and winter were characterised by lower than average temperatures and higher than average rainfall.

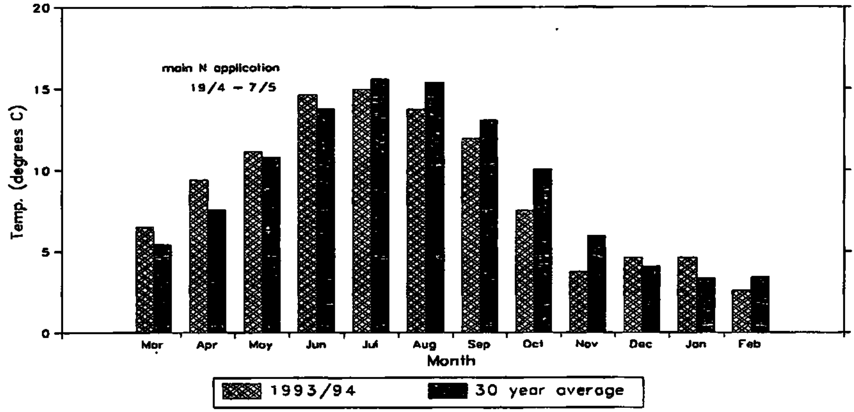


Figure 3.6 Comparison between mean monthly temperatures March 1993 to February 1994 and the 30 year mean (1961-1990)

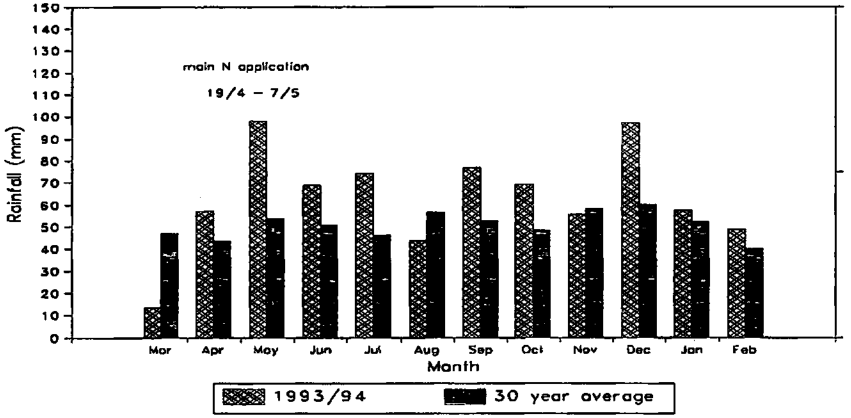


Figure 3.7 Comparison between mean monthly rainfall March 1993 to February 1994 and the 30 year mean (1961-1990)

Grain Yield

A response to N was recorded; on average N significantly increased grain yield by 5.57 t/ha compared to the zero N treatment (Table 3.13). Yield differences between N treatments were not significant.

Above Ground Dry Matter Production

On average, N significantly increased above ground dry matter production compared to the zero N treatment (Table 3.13). Above ground dry matter production was not significantly different between the ammonium nitrate treatment (16.4 t/ha) and the mean of the urea treatments (17.4 t/ha).

Within the urea treatments, above ground dry matter production increased as the rate of N applied as foliar urea increased, up to 90 kg N/ha as foliar urea and then decreased again. This trend was significant.

Harvest Index (Table 3.13)

On average, N significantly increased harvest index compared to the zero N treatment. Harvest index was not significantly different between the ammonium nitrate treatment (0.58) and the urea treatments on average (0.54). Within the urea treatments, as the rate of N applied as foliar urea increased, harvest index decreased for 60 kg N/ha as foliar urea and then increased again up to 170 kg N/ha as foliar urea. This quadratic trend was significant.

Table 3.13 Grain yield, above ground dry matter production and harvest index in the main experiment 1993

Treatment	Grain yield (t/ha)	Above ground dry matter (t/ha)	Harvest index
Zero N	3.68	8.09	0.457
Ammonium nitrate	9.53	16.43	0.582
Solid urea	8.98	16.69	0.555
30 kg N/ha foliar urea	9.52	16.75	0.572
60 kg N/ha foliar urea	8.86	17.97	0.506
90 kg N/ha foliar urea	9.52	19.17	0.508
120 kg N/ha foliar urea	8.99	17.32	0.528
170 kg N/ha foliar urea	9.45	16.3	0.584
S.E.M.	0.275	0.943	0.0288
C.V. (%)	6.4	11.7	10.7

Scorch

Percentage scorch, as recorded five days after the final spray application for each of the foliar urea treatments, was low, less than 5% in all cases (Table 3.14). There was no significant difference in scorch between foliar treatments following any of the foliar urea applications.

Table 3.14 Scorch 5 days following each foliar fertiliser application in the main experiment 1993

Treatment	% Scorch			
	Spray 1	Spray 2	Spray 3	Spray 4
30 kg N/ha foliar urea	1.66			
60 kg N/ha foliar urea	1.17	0.823		
90 kg N/ha foliar urea	1.07	0.991	0.565	
120 kg N/ha foliar urea	2.08	0.891	0.944	1.05
170 kg N/ha foliar urea	1.68	0.766	0.839	1.20
S.E.M.	0.377	0.1672	0.1534	0.145
C.V. (%)	49.1	38.5	39.2	25.8

Growth Analysis

Shoot Production (Table 3.15)

Maximum shoot production was recorded for all treatments in the last week of April. With the exception of the first two sample dates, nitrogen treatment on average significantly increased shoot production. In early April and early May, shoots/m^2 were significantly higher for the ammonium nitrate treatment than for the urea treatments on average. In early May, within the urea treatments, shoots/m^2 decreased significantly as the rate of N applied as foliar urea increased. There were no other significant differences in shoot production between N treatments on any of the sample dates and there was no indication from the data that N treatment affected shoot survival.

Table 3.15 Live shoots/m^2 in the main experiment 1993

Treatment	Shoots / m^2									
	April	April	April	April	May	May	May	May	June	June
	4	14	23	28	5	12	21	28	4	11
Zero N	735	746	768	796	711	593	477	429	378	365
Ammonium nitrate	858	864	993	1012	1010	896	754	712	660	570
Solid urea	738	812	920	936	928	847	738	700	618	554
30 kg N/ha foliar urea	738	781	936	975	959	881	770	710	616	543
60 kg N/ha foliar urea	772	838	966	1016	1013	928	826	778	682	603
90 kg N/ha foliar urea	745	793	903	1032	900	886	762	726	606	546
120 kg N/ha foliar urea	734	763	915	916	883	790	689	652	572	516
170 kg N/ha foliar urea	772	808	925	949	824	783	712	691	595	551
S.E.M.	36.2	41.6	31.4	43.5	39.5	34.1	33.9	34.2	23.5	24.8
C.V. (%)	8.2	9	5.9	7.9	7.6	7.2	8.2	8.8	6.9	8.1

Dry Matter Production (Table 3.16)

Compared to the zero N treatment, nitrogen on average, significantly increased total dry matter, stem dry matter, leaf dry matter, flag leaf dry matter and ear dry matter on all three sample dates. There was no significant difference between the ammonium nitrate treatment and the mean of the urea treatments on any of the sample dates.

Within the urea treatments, dry matter production was not significantly different between treatments on the 9/5/93. On the 12/6/93, total dry matter, stem dry matter and leaf dry matter increased up to 90 kg N/ha as foliar urea before decreasing again. This trend was significant for leaf and stem dry matter.

On the 16/7/93, total dry matter, stem dry matter, flag leaf dry matter and ear dry matter decreased significantly as the rate of N applied as foliar urea increased. No significant trend within the urea treatments was recorded for leaf dry matter on this date, the high variability of the data (c.v. 64.7%) would have contributed to the lack of significance.

<u>Green Area</u> (Table 3.17)

Compared to the zero N treatment, nitrogen on average, significantly increased total green area index, stem area index, leaf area index, flag leaf area index and ear green area index on all three sample dates. With the exception of ear green area index on the 16/7/93, there were no significant differences between the ammonium nitrate treatment and the mean of the urea treatments on any of the sample dates with respect to these components of green area. On the 16/7/93 ear green area index was significantly higher for the urea treatments on average than for the ammonium nitrate treatment.

Within the urea treatments, as the rate of N applied as foliar urea increased, there was no significant trend in total green area index on the 9/5/93. While stem area index decreased significantly as the rate of N applied as foliar urea increased, there was no significant trend in leaf area index.

On the 12/6/93 total green area index, stem area index, leaf area index, flag leaf area index and ear green area index increased as the rate of N applied as foliar urea increased up to 90 kg N/ha as foliar urea and then decreased again. This quadratic trend was significant in all cases.

On 16/7/93, as the rate of N applied as foliar urea increased, total green area index, stem area index, leaf area index, flag leaf area index and ear green area index decreased. With the exception of flag leaf area index, these trends were significant.

Table 3.16 Dry matter production in the main experiment 1993

	Dry matter (t/ha)															
	9/5/93				12/6/93						16/7/93					
Treatment	Stem	Leaf	Dead	Total	Stem	Leaf	Flag	Ear	Dead	Total	Stem	Leaf	Flag	Ear	Dead	Total
Zero N	0.969	0.678	0.075	1.721	3.31	0.383	0.125	0.825	0.340	4.99	2.596	0.053	0.065	3.600	0.798	7.11
Ammonium nitrate	1.911	1.573	0.095	3.579	5.97	1.001	0.347	1.580	0.717	9.61	5.712	0.336	0.347	7.957	1.007	15.36
Solid urea	1.996	1.528	0.095	3.620	4.97	0.827	0.307	1.370	0.445	7.92	6.438	0.330	0.362	8.665	1.180	16.98
30 kg N/ha foliar urea	2.061	1.45	0.149	3.66	5.37	0.854	0.301	1.476	0.455	8.46	6.168	0.338	0.395	8.507	1.008	16.42
60 kg N/ha foliar urea	1.972	1.489	0.090	3.552	6.29	1.025	0.376	1.781	0.536	10.01	6.635	0.402	0.419	8.651	0.954	17.06
90 kg N/ha foliar urea	1.844	1.44	0.089	3.373	6.76	1.183	0.462	1.897	0.419	10.72	6.218	0.330	0.391	8.561	1.040	16.54
120 kg N/ha foliar urea	2.102	1.548	0.134	3.784	6.45	1.143	0.414	1.869	0.450	10.32	6.004	0.221	0.331	8.6	1.105	16.26
170 kg N/ha foliar urea	1.827	1.412	0.154	3.398	5.93	1.011	0.398	1.709	0.482	9.54	5.287	0.413	0.242	7.772	0.954	14.67
S.E.M.	0.0875	0.0761	0.0285	0.1509	0.502	0.0777	0.0453	1.1505	0.1159	0.830	0.2299	0.1132	0.0474	0.249	0.1049	0.531
C.V. (%)	8.3	9.5	44.5	7.8	15.4	14.5	23.0	16.7	41.8	16.1	7.1	64.7	25.7	5.5	18.1	6.1

Table 3.17 Green area in the main experiment 1993

	Green area index												
	9/5/93			12/6/93					16/7/93				
Treatment	Stem	Leaf	Total	Stem	Leaf	Flag	Ear	Total	Stem	Leaf	Flag	Ear	Total
Zero N	0.1532	1.153	1.306	0.459	0.860	0.331	0.162	1.81	0.362	0.128	0.141	0.1897	0.821
Ammonium nitrate	0.3939	3.183	3.577	0.922	2.197	0.759	0.327	4.21	0.965	0.601	0.565	0.4318	2.564
Solid urea	0.4016	2.99	3.392	0.794	1.847	0.681	0.284	3.61	1.092	0.610	0.607	0.4949	2.804
30 kg N/ha foliar urea	0.3948	3.018	3.413	0.868	1.927	0.665	0.037	3.77	1.036	0.639	0.687	0.4756	2.838
60 kg N/ha foliar urea	0.3994	2.793	3.192	1.025	2.308	0.840	0.365	4.54	1.079	0.705	0.593	0.4621	2.839
90 kg N/ha foliar urea	0.3510	2.903	3.254	1.163	2.744	1.032	0.407	5.35	1.043	0.620	0.644	0.4797	2.786
120 kg N/ha foliar urea	0.3641	2.717	3.081	1.063	2.584	0.906	0.385	4.94	1.013	0.404	0.548	0.4696	2.434
170 kg N/ha foliar urea	0.3151	2.632	2.947	0.983	2.339	0.860	0.357	4.54	0.875	0.352	0.437	0.4227	2.088
S.E.M.	0.02439	0.2581	0.2779	0.0858	0.1777	0.0881	0.0300	0.368	0.0403	0.1106	0.0810	0.01311	0.2163
C.V. (%)	12.2	16.7	15.9	16.3	14.7	20.1	16.0	15.6	7.5	37.7	26.6	5.3	15.6

Above Ground Plant N (kg/ha in the dry matter) and N Content (%) (Table 3.18)

Nitrogen treatment on average significantly increased N in the above ground plant material compared to the zero N treatment. Above ground plant N was not significantly different between ammonium nitrate and the mean of the urea treatments. Within the urea treatments, above ground plant N increased up to 90 kg N/ha applied as foliar urea, and then decreased again, however, this trend was not significant.

Differences in above ground plant N are largely a reflection of differences in above ground dry mater production, differences in N concentration in the dry matter (% N) being small. There was no significant difference in N content between the ammonium nitrate treatment and the urea treatments on average or within the urea treatments as the rate of N applied as foliar urea increased.

Grain N Concentration (Table 3.18)

N application, on average, significantly increased grain N concentration. Ammonium nitrate significantly increased grain N concentration compared to urea treatment on average. Within the urea treatments, grain N concentration decreased significantly as the rate of N applied as foliar urea increased.

Apparent Nitrogen Recovery (Table 3.18)

Apparent N recovery was not significantly different for ammonium nitrate (74%) and the urea treatments on average (77%). Within the urea treatments, apparent N recovery increased as the rate of N applied as foliar urea increased up to 90 kg N/ha as foliar urea and then decreased, however, this trend was not significant.

Table 3.18 Above ground N and apparent N recovery in the main experiment 1993

Treatment	Above ground plant N		Grain N (%)	Above ground apparent N recovery
	%	kg N/ha		(%)
Zero N	0.946	76.5	1.83	-
Ammonium nitrate	1.224	202.5	2.184	74.1
Solid urea	1.185	198.3	2.144	71.6
30 kg N/ha foliar urea	1.099	182.2	2.139	62.2
60 kg N/ha foliar urea	1.160	210.8	2.099	79.0
90 kg N/ha foliar urea	1.265	243.5	2.084	98.2
120 kg N/ha foliar urea	1.176	204.4	2.059	75.2
170 kg N/ha foliar urea	1.211	197.1	2.014	70.9
S.E.M.	0.0537	16.59	0.0151	10.31
C.V. (%)	9.3	17.5	1.5	27.2

Soil Mineral N (Table 3.19)

In the autumn, total soil mineral N to 90 cm and soil mineral N in each of the horizons sampled was not significantly different for the zero N plots and the N treatments on average, or for the ammonium nitrate treatment and the urea treatments on average.

Within the urea treatments, there was no significant trend in total soil mineral N to 90 cm with increasing rate of N applied as foliar urea. Soil mineral N in the 0-15 cm horizon showed a significant quartic variation as the rate of N applied as foliar urea increased. There was no significant trend in the other horizons and mineral N in these horizons compensated for the differences in the 0-15 cm horizon in the total mineral N to 90 cm.

In the following spring total soil mineral N to 90 cm and mineral N in each of the horizons measured was not significantly different for the zero N treatment and the nitrogen treatments on average or for the ammonium nitrate and the urea treatments on average. Within the urea treatments there was no significant trend in soil mineral N.

Table 3.19 Soil mineral N to 90 cm in the main experiment in autumn 1993 and spring 1994

Treatment	Soil mineral N (kg/ha)									
	Autumn					Spring				
	0-15 cm	15-30 cm	30-60 cm	60-90 cm	Total	0-15 cm	15-30 cm	30-60 cm	60-90 cm	Total
Zero N	13.9	14.7	16.4	14.9	60.0	10.3	10.4	10.2	11.8	42.7
Ammonium nitrate	12.4	16.5	20.2	16.8	65.9	11.9	12.9	16.3	12.6	53.7
Solid urea	15.5	15.2	15.9	19.9	64.6	10.7	12.2	10.1	10.6	43.7
30 kg N/ha foliar urea	16.2	17.3	17.7	17.4	68.5	10.7	12.2	13.6	14.8	51.4
60 kg N/ha foliar urea	13.3	14.1	18.4	17.7	63.5	9.0	9.7	9.8	13.2	41.7
90 kg N/ha foliar urea	12.9	14.8	17.9	19.9	65.5	13.2	14.1	15.6	16.8	59.7
120 kg N/ha foliar urea	15.2	16.4	20.2	16.7	68.5	13.4	12.5	11.3	12.7	50.0
170 kg N/ha foliar urea	11.4	16.0	13.1	15.6	56.1	10.5	12.9	13.5	8.4	45.3
S.E.M.	1.28	1.27	2.41	1.59	4.38	1.54	1.47	2.55	3.17	6.44
C.V. (%)	18.9	16.3	27.5	18.3	13.7	27.5	24.3	40.5	50.1	26.5

Calculation of the apparent recovery of fertiliser N in the soil mineral N fraction in the autumn allows a crude apparent N balance to be calculated for the plant-soil mineral N system, this is shown in Table 3.20.

Table 3.20 Apparent N balance for the main experiment 1993

Treatment	Apparent N recovery (%)			Net loss / gain(%)
	Above ground crop	Autumn soil mineral N (to 90 cm)	Total	
Ammonium nitrate	74.1	3.5	77.6	-22.6
Solid urea	71.6	2.7	74.3	-25.7
30 kg N/ha foliar urea	62.2	5.0	67.7	-32.3
60 kg N/ha foliar urea	79.0	2.1	81.1	-18.9
90 kg N/ha foliar urea	98.2	3.2	101.4	+1.4
120 kg N/ha foliar urea	75.2	5.0	80.2	-19.8
170 kg N/ha foliar urea	70.9	-2.3	68.6	-31.4

C/N Ratio of Incorporated Straw (including chaff)

N application, on average, significantly reduced the C/N ratio of the straw + chaff fraction returned to the plots after harvest (Table 3.21). The C/N ratio of the straw + chaff from the urea treatments on average, was significantly higher than for the ammonium nitrate treatment. Within the urea treatments, the C/N ratio of the straw + chaff significantly increased as the rate of N applied as foliar urea increased.

Table 3.21 C/N ratio of straw + chaff fraction returned to the soil in the main experiment 1993

Treatment	C/N ratio of straw + chaff
Zero N	159.2
Ammonium nitrate	99.47
Solid urea	103.0
30 kg N/ha foliar urea	112.1
60 kg N/ha foliar urea	110.5
90 kg N/ha foliar urea	103.6
120 kg N/ha foliar urea	114.2
170 kg N/ha foliar urea	124.7
S.E.M.	5.17
C.V. (%)	8.9

Nitrate Leaching in the Subsequent Winter

Figure 3.8 shows the nitrate concentration in the soil water at 1 m for each treatment over the subsequent winter. Peak nitrate concentration occurred for all treatments in early December.

Mean soil water nitrate concentration and quantity of nitrate-N leached over the subsequent winter is shown in Table 3.22. Nitrogen application, on average, significantly increased mean soil water nitrate concentration (103.8 mg/l v 76.8 mg/l) and estimated nitrate-N leached (54.8 kg/ha v 40.5 kg/ha).

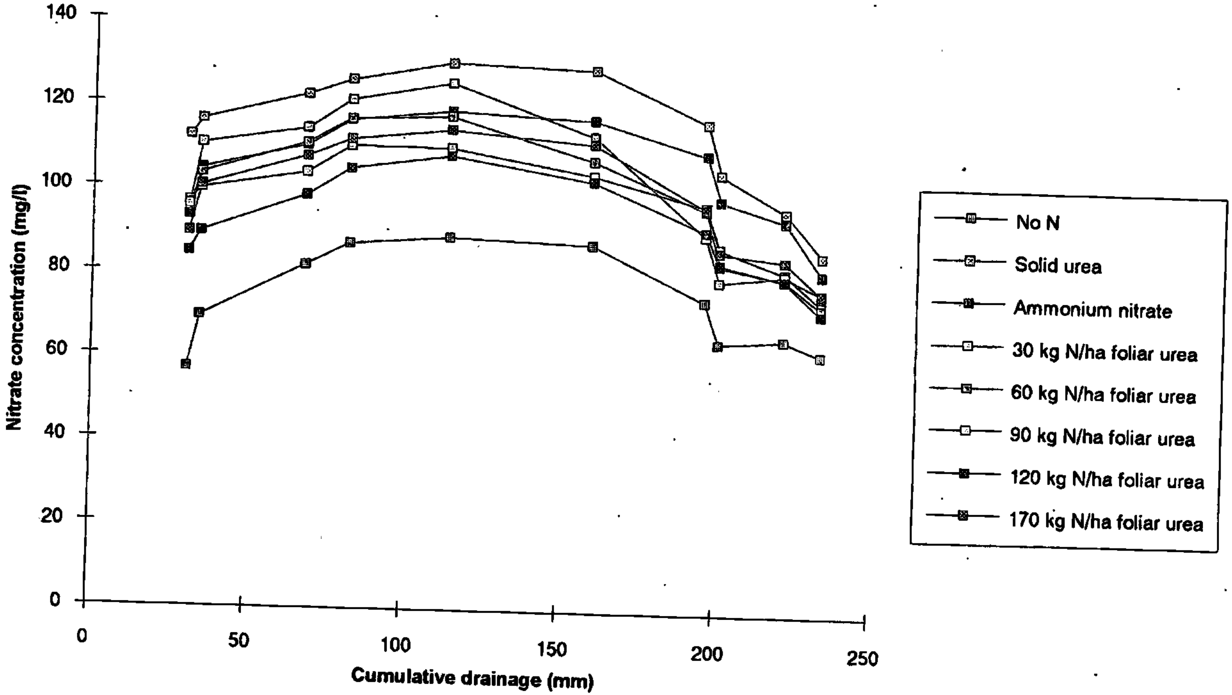


Figure 3.8 Soil water nitrate concentrations over winter 1993/94 for 170 kg N/ha applied as ammonium nitrate and as different proportions of foliar urea in the main experiment

Table 3.22 Mean soil water nitrate concentration and nitrate-N leached in the drainage water over winter 1993/94 in the main experiment

Treatment	Mean nitrate concentration in soil water (mg/l)	Nitrate-N leached (kg/ha)
Zero N	76.8	40.52
Ammonium nitrate	118.2	62.3
Solid urea	107.5	56.7
30 kg N/ha foliar urea	99.2	52.3
60 kg N/ha foliar urea	101.9	53.7
90 kg N/ha foliar urea	104.2	55.0
120 kg N/ha foliar urea	94.5	49.9
170 kg N/ha foliar urea	101.3	53.4
S.E.M.	6.69	3.53
C.V. (%)	13.3	13.3

Average nitrate concentration and estimated quantity of nitrate-N leached over winter was significantly higher for the ammonium nitrate treatment than for the urea treatments on average. Within the urea treatments there was no significant trend in nitrate concentration or quantity of nitrate-N leached as the rate of N applied as foliar urea increased.

3.2.4 Discussion

Yield, Above Ground Dry Matter and Harvest Index:

Mean grain yield for the nitrogen treatments was some 2 t/ha above the average wheat yield for the West Midlands area (MAFF, 1994d). In contrast to 1992, this year yield was not significantly different for ammonium nitrate treatment and the urea treatments on average. This supports the conclusion that the reduced yield with ammonium nitrate in 1992 was anomalous, probably attributable to leaching of the more mobile nitrate ion beyond the root zone following particularly heavy rainfall following the main N application.

For the second year, the generally inferior yield response to N as urea compared to ammonium nitrate, as reported in literature (Van Burg, 1986; Chaney & Paulson, 1988), and the yield reduction for N as foliar urea as reported by Poulton *et al.* (1990) was not observed in this experiment. With respect to the latter, severe leaf scorch was implicated as a contributory factor in the yield reduction. Scorch levels for the foliar urea treatments in this experiment were low, less than 5%, and as such unlikely to affect yield (Dampney & Salmon, 1990; Warden & Kettlewell, 1993).

The quadratic trend in above ground dry matter production as the rate of N applied as foliar urea increases is in contrast to the linear decrease observed in 1992. With respect to harvest index, while there was evidence of an increase as the rate of N applied as foliar urea increased, as in 1992, the effect was less pronounced and the largest effect was only apparent for those treatments receiving a larger proportion of N as foliar urea and therefore that would have received a proportion of N later.

Grain yield is a function of above ground dry matter production and harvest index. From the 1993 data, foliar urea appears to affect yield by influencing both above ground dry matter production and harvest index, and it appears to be compensatory in these two effects; an increase in above ground dry matter production being offset by a decrease in harvest index and *vice versa*, such that yield is maintained.

Further, the results suggest that the balance between above ground dry matter production and harvest index is determined by time of application: where the rate of N applied as foliar urea is relatively low and therefore a larger proportion of the total N is applied early, above ground dry matter production is increased but a smaller proportion of this dry matter is partitioned to the grain (reduced harvest index). For those treatments receiving a higher rate of N as foliar urea (120 kg N/ha and 170 kg N/ha as foliar urea) and therefore that receive a proportion of the total N application later, above ground dry matter production is reduced, but the dry matter is partitioned more efficiently to the grain (increased harvest index) and yield is maintained. That the physiological response of winter wheat to foliar urea is due to compensatory effects on above ground dry matter production and harvest index according to time of application is supported by the 1992 data. Figure 3.9 shows the timing of the foliar urea applications for 1992 and 1993 in relation to crop development. Crop development was similar in both years, the crop reached GS 31 around the 20 April in both years, however, due to bad weather, application of foliar urea sprays was considerably delayed in 1992 compared to 1993, consequently, even those treatments receiving a smaller proportion of N as foliar urea (e.g. 30 kg N/ha and 60 kg N/ha as foliar urea) received a relatively late application of foliar urea compared to 1993. The effect of the delayed application in 1992 was to reduce above ground dry matter production and increase harvest index even for those treatments receiving a relatively small proportion of total N as foliar urea.

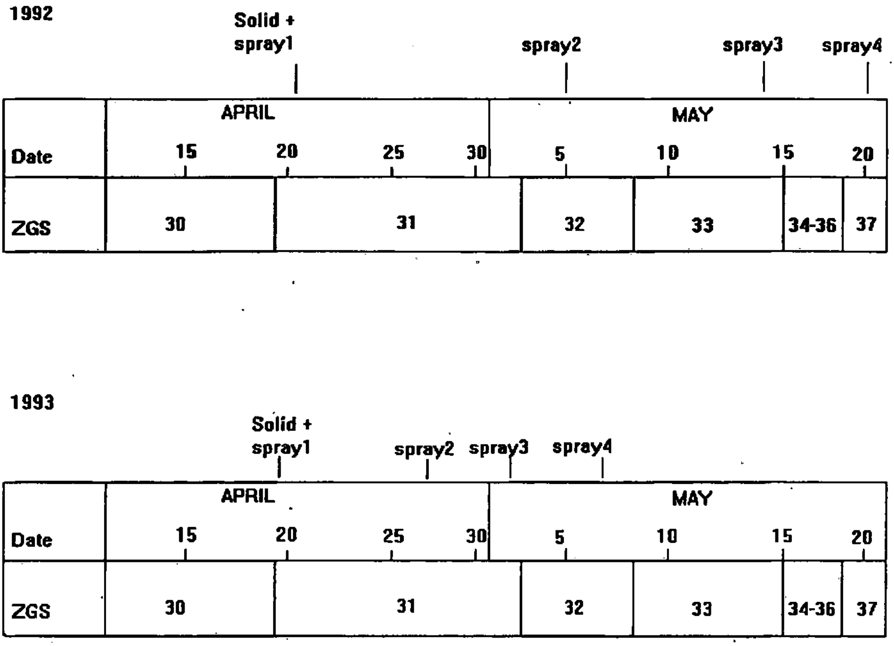


Figure 3.9 Time of application of foliar urea sprays in 1992 and 1993 in the main experiment

The effect of time of application of N on above ground dry matter production recorded here, is in accordance with the generally recognised effect of N timing on above ground dry matter production as reported in the literature: early N, due to effects on tiller production and leaf growth, stimulates vegetative growth; while later applications, due to effects on tiller survival, grain set and leaf area duration, influence harvest components with little effect on vegetative growth (Gallagher and Biscoe, 1978b; Spiertz *et al.*, 1984). The effect of N timing on harvest index has also been reported by others: small increases in harvest index associated with delayed N application between GS 32 and 39 have been reported by McLaren (1981) and Darwinkel (1983).

Growth Analysis Measurements

The trend in above ground dry matter production across the nitrogen treatments on 12 June and 16 July, correlates well with the trend in above ground dry matter recorded at harvest.

A green area index of five is considered optimal for cereals, intercepting 90% of the incident radiation (Sylvester-Bradley and Scott, 1990). Given the high dry matter production and high grain yields recorded in this experiment, the peak green area indices are therefore slightly lower than expected.

Gallagher & Biscoe (1978a) have demonstrated a strong correlation between the rate of dry matter production and the amount of intercepted radiation. Intercepted radiation is a function of incident radiation and green area index. In this experiment, the trend in green area index around anthesis on 12 June was closely correlated with the trend in above ground dry matter production at harvest. Green area index is a function of shoot population and leaf size. Shoot population in turn is a function of plant establishment in the spring, tiller production and tiller survival; while leaf size is a function of leaf expansion and leaf persistence.

In early spring there was no significant difference in established plant populations between N treatments. Further, there was no significant difference in peak shoot populations and no indication from the data that N treatment affected shoot survival.

The lack of any significant difference in shoot populations between the urea treatments indicates that the significant quadratic trend in green area index around anthesis is due to the rate of N applied as foliar urea affecting the size of green leaves and stem. Leaf area as expected, constituted the main component of total green area at this time and the trend in green area index within the urea treatments shows a good correlation with total leaf area and flag leaf area. The data suggests therefore, that rate of N applied as foliar urea affects green area index mainly by influencing leaf size.

Due to the method of sampling, it is difficult to determine from the data whether the effect of leaf size was due to the rate of N applied as foliar urea affecting rate of leaf expansion or rate of leaf senescence i.e. leaf persistence, or both. However, consideration of the flag leaf green area on 12 June and on 16 July shows the reduction in flag leaf green area to be similar over the urea treatments. This suggests that the rate of N applied as foliar urea does not affect leaf persistence. The results suggest therefore that effects on above ground dry matter production at harvest are due to differences in green area index at anthesis largely attributable to differences in leaf area, due to the treatments influencing leaf expansion rather than leaf persistence.

As the rate of N applied as foliar urea increases, green area index around anthesis and above ground dry matter at harvest increased up to a maximum for 90 kg N/ha as foliar urea and then decreased for 120 and 170 kg N/ha as foliar urea. The 120 and 170 kg N/ha foliar urea treatments received their final 30 kg N/ha five days after the final foliar urea application to the 90 kg N/ha foliar treatment. The results suggest therefore, that the reduction in above ground dry matter at harvest for those treatments receiving a larger proportion of N as foliar urea, is due to the final 30 kg N/ha being applied later and used less efficiently to produce green leaf area; i.e. the effect on leaf expansion is one of timing rather than form of N applied.

No measurements were taken in this experiment to determine the basis of the increase in harvest index as the rate of N applied as foliar urea increased. Harvest index is a function of grain yield and total above ground dry matter production. Grain yield in turn, is a function of shoots bearing ears at harvest, ear development in terms of spikelet and floret formation and spikelet and floret survival, and grain filling. For those treatments that showed an increase in harvest index i.e. 120 and 170 kg N/ha as foliar urea, the last 30 kg N/ha was applied at GS 32 on the 7 May. The start of floret death as reported in the literature ranges from GS 32-39 (Gallagher and Biscoe, 1978b; Baker and Gallagher, 1983; Barling, 1982). The final application of foliar urea to these treatments would therefore have coincided approximately with the start of floret death. It is logical therefore to speculate, that the increase in harvest index for those treatments receiving a larger proportion of N as foliar urea is due to the later 30 kg N/ha application offsetting floret death and thereby increasing partitioning of the dry matter to the grain. Again, a timing effect rather than form of N applied is implicated. The increase in grains per fertile spikelet recorded for N applied from floret initiation to ear emergence (Single, 1964; Langer and Liew, 1973; Darwinkel, 1983) together with the lack of any effect of N on floret production (Langer and Hanif, 1973; Whingwiri and Stern, 1982), and therefore the implied effect of N in reducing floret abortion, was noted in the literature review. Peltonen (1992) recorded a maximum effect on floret numbers for 20 kg N/ha of supplementary N applied as foliar urea around GS 39 under glasshouse conditions. Grains per ear and grain yield were increased, however, total above ground dry matter also increased and no effect on harvest index was recorded.

Apparent Nitrogen Recovery

Apparent recovery of fertiliser N in the above ground crop for all treatments is higher than that commonly reported in the literature, but similar to that recorded in 1992. In contrast to the significant quadratic decrease in apparent N recovery within the urea treatments recorded in 1992, no significant trend was found this year.

Apparent N recovery for the all foliar urea treatment was higher this year. Volatilisation and / or denitrification losses associated with the early 50 kg N/ha applied as foliar urea together with the consequent poor crop growth leading to higher losses from subsequent applications were implicated for the low apparent N recovery for the all foliar urea treatment in 1992. The early foliar urea applications around GS 21, were made early in the day in 1992 but in the evening in 1993. The influence of temperature and windspeed on rate of ammonia volatilisation and that of temperature on denitrification was noted in the literature review (Haynes and Sherlock, 1986). It is likely that lower temperatures and windspeeds overnight following application in the evening, would have been less conducive to gaseous losses following hydrolysis, for the early foliar urea application this year compared to 1992. A marked diurnal pattern in the rate of ammonia volatilisation, predominantly related to temperature, has been reported by a number of workers (Haynes and Sherlock, 1986). With respect to the main nitrogen application, due to the tighter spray programme at GS 31 this year, the foliar urea treatments received a larger proportion of their main foliar application earlier, in cooler conditions. Further, these applications were also largely applied in the evening this year. That proportion of the main spring N application applied as foliar urea would therefore have also been applied under conditions less conducive to gaseous losses this year compared to 1992.

It is therefore likely that the lack of any significant trend in apparent N recovery for N applied as foliar urea this year, compared to 1992, is attributable to reduced gaseous losses due to earlier application under cooler conditions.

While there were no significant trends in apparent N recovery within the urea treatments, apparent N recovery for the 90 kg N/ha foliar urea treatment was high, approaching 100%, compared to the other urea treatments. The higher apparent N recovery for this treatment is a reflection of the higher above ground dry matter production and higher N concentration in the dry matter.

The reduction in grain N concentration as the rate of N applied as foliar urea increased, is similar to the trend observed in 1992 for this experiment and agrees with Poulton *et al.* (1990) who reported a lower concentration of N in the grain for foliar N compared to soil applied N.

Soil Mineral N

The soil mineral N values are in the order reported elsewhere for soil mineral N in the autumn (Jenkinson, 1986; Goulding & Webster, 1992; Harris & Rose, 1992; Harrison, 1995) and in the spring (Chambers, 1992a).

The mean soil mineral nitrogen to 90 cm in the autumn, 64 kg N/ha (mean soil mineral N to 90 cm all N treatments), was lower than that recorded for the site in 1992, while that recorded in the spring, 49 kg N/ha, was similar. The lower autumn soil mineral N levels this year may be related to the generally higher C/N ratio of incorporated straw and chaff, which would favour increased immobilisation of N in the soil organic matter. Further, the interval between ploughing and soil sampling was longer this year, allowing more time for immobilisation before the autumn soil samples were taken.

In 1992, a significant linear decrease in soil mineral N in the autumn was recorded as the rate of N applied as foliar urea increased. It was tentatively suggested that this was related to the significant increase in C/N ratio of the incorporated straw and chaff, favouring immobilisation of N in the soil organic matter as the proportion of N applied as foliar urea increased. This year, there was no significant decrease in autumn soil mineral N as the rate of N applied as foliar urea increased. Due to similar apparent N recovery for the treatments, particularly the all foliar urea treatment, the increase in C/N ratio of the incorporated straw and chaff with increasing rate of N applied as foliar urea was not as great this year. It is logical to expect therefore, that the increase in immobilisation as the rate of N applied as foliar urea increased would have been lower this year, resulting in similar soil mineral N in the autumn for the urea treatments. A limitation of this hypothesis is likely to be the rate of mineralisation / immobilisation in relation to the time interval between straw incorporation and soil sampling in the autumn.

The distribution of soil mineral N to 90 cm in the autumn was different to that recorded in 1992. A higher proportion of the mineral N was in the lower horizons this year: 45% of the mineral N to 90 cm was in the 0-30 cm horizon, and smaller equal proportions, 27%, in the 30-60 and 60-90 cm horizons (mean data for all treatments). The higher proportion of mineral N in the lower horizon this year compared to 1992 may be attributed to greater leaching of mineral N down the profile, due to heavy rainfall in the autumn prior to sampling this year compared to 1992. Chaney (1990) has reported a similar distribution, but with a continual decrease down the profile rather than approximately equal proportions in the lower horizons as found here.

From the apparent mineral N balance presented in Table 3.20, with the exception of the all foliar urea treatment, apparent recovery of fertiliser N in the crop-soil mineral N system for the N treatments is generally lower than in 1992. This is due to the generally lower apparent recovery of fertiliser N in the soil mineral N fraction this year compared to 1992, apparent recovery in the crop being similar. Apparent recovery of fertiliser N in the crop-soil mineral N system for the all foliar urea treatment was substantially higher this year due to the higher apparent N recovery by the crop.

Nitrate Leaching

Autumn soil mineral N indicates the quantity of mineral N potentially at risk to leaching over the subsequent winter. The lower autumn soil mineral N for the nitrogen treatments in general this year compared to 1992, was compensated for by increased cumulative over winter drainage, and weight of nitrate-N leached over the subsequent winter was only slightly lower this year.

With the exception of the ammonium nitrate treatment, nitrate leaching over the winter reflects soil mineral N in the autumn for the treatments. For the ammonium nitrate treatment, however, soil mineral N in the autumn was not significantly different to the urea treatments on average, but quantity of nitrate-N leached and mean concentration of nitrate in the soil water over the subsequent winter was significantly higher. This may have been attributable to lower immobilisation in these plots after soil sampling in the autumn, associated with the lower C/N ratio of the incorporated straw and chaff for the ammonium nitrate treatment compared to the urea treatments on average. It is likely that the wet autumn would have been conducive to continued mineralisation / immobilisation turnover following soil sampling. While quantity of nitrate-N leached over the winter was lower this year compared to 1992/93, losses are still higher compared to the average 20 kg nitrate-N/ha per year for sandy soil in continuous arable production as reported by others (Goulding & Poulton, 1992; Davies and Archer, 1990). Twice this quantity of nitrate-N leached from the zero N plots alone. Drainage has a major effect on N leaching losses. Cumulative drainage over the winter this year was 233 mm compared to 157 mm recorded for the 1992/93 winter. Goulding and Poulton (1992) cite the variation in loss of 10 & 51 kg N/ha per year as nitrate from a sandy soil in continuous cereals for 140 mm and 330 mm of drainage. The leaching losses recorded in this experiment are therefore still higher than expected given the cumulative drainage. With the exception of the zero N treatment and the all foliar urea treatment, the mean nitrate concentration in the soil water draining from the plots was lower this year than in 1992/93. This was a reflection of the generally lower quantity of nitrate-N leached from the treatments and the higher cumulative drainage volume causing a dilution effect. The nitrate concentration in the drainage water from the zero N treatment and the all foliar urea treatment was higher this year due to the increased quantity of nitrate-N leached more than compensating for the increase in drainage volume.

Despite the generally lower quantity of nitrate-N leached and increased drainage, the mean soil water nitrate concentrations recorded for all of the N treatments are still approximately two times the EU limit (Council for European Communities, 1980 & 1991).

3.3 MAIN EXPERIMENT 1994

In the main experiment carried out in 1992 and 1993 foliar urea maintained yield due to compensatory effects on above ground dry matter production and harvest index, and the results indicated that the balance between the two effects was determined by time of application.

The effect of foliar urea on above ground dry matter production appeared to be due to differences in green area index at anthesis, related to differences in leaf area index, due to foliar urea affecting rate of leaf expansion rather than leaf persistence. The effect may be due to foliar urea affecting growth of the canopy in general or particular leaves within it. A more detailed growth analysis was therefore carried out in this respect.

No measurements were taken in year 1 or 2 to determine the basis of the effect of foliar urea on harvest index, however, from the second year data, it was speculated that the effect may be due to later applications of foliar urea offsetting floret death and thereby increasing partitioning of the dry matter to the grain. An analysis of the components of grain yield at harvest was therefore carried out to determine the basis of the effect of foliar urea on harvest index.

Nitrate leaching recorded in the year 1 and 2 was considerably higher than expected. No estimate of the potential contribution to nitrate leaching of atmospheric N inputs at the site has been made. Other studies have indicated a gross N deposition from the atmosphere in the order of 35 - 48 kg N/ha to arable land (Goulding, 1990; Jenkinson, 1982; Powlson *et al.*, 1986a). An indication of atmospheric N input at the site was therefore required.

The objectives of the main experiment in the third year were therefore:

1) To repeat the experiment using the same plots for a third year, to account for seasonality effects, particularly with respect to soil mineral N and nitrate leaching data.
2) To extend the anthesis growth analysis to examine individual leaves within the canopy, to determine whether the effect of foliar urea on green area index can be related to effects on leaf area index of specific leaves within the canopy. Further, to measure intercepted radiation at anthesis to support the growth analysis data.
3) To record ears/m^2, grains/ear and grain weight at harvest, to determine the basis of the effect of foliar urea on harvest index.
4) To measure NH_4^+ and NO_3^--N in rainfall, to determine the potential contribution of inorganic N in rainfall to nitrate leaching at the site, as an indication of atmospheric N deposition at the site.

3.3.1 Field Treatments

The Little Pipe Strine site was redrilled with winter wheat (*Triticum aestivum* cv. Beaver) on 16 October 1993. Seedbed cultivations were as for 1992. Baytan treated C2 seed was used and drilled with a row spacing of 12.4 cm. Seedbed fertiliser consisted of 37 kg/ha phosphate (P_2O_5) and 56 kg/ha potash (K_2O), as in previous years.

The experimental site was recovered by triangulation, such that each plot occupied the same position in the field as in year 1 and 2 (Figure 3.1). Nitrogen treatments were as in year 1 and 2 (Table 3.1), such that each plot received the same N treatment as in the previous two years. Details of N applications were as given previously. Actual dates and growth stages of applications are given in Table 3.23.

Table 3.23 Dates of N applied in the main experiment 1994

		TREATMENT							
ZGS	Date Applied	Zero-N	NH_4NO_3 (kg N/ha)	Solid urea (kg N/ha)	30 kg N/ha Foliar urea	60 kg N/ha Foliar urea	90 kg N/ha Foliar urea	120 kg N/ha Foliar urea	170 kg N/ha Foliar urea
22	10/3								30F
22	12/3		50	50S	50S	50S	50S	50S	-
22/23	16/3								20F
31	28/4				30F	30F	30F	30F	30F
31	30/4		120	120S	90S	60S	30S	-	-
31	2/5					30F	30F	30F	30F
32	6/5						30F	30F	30F
33	12/5							30F	30F
Total		0	170	170	170	170	170	170	170

S = Urea applied as solid F = Urea applied as foliar spray

3.3.2 Sampling and Analytical Techniques

Shoot Counts

Shoot counts were limited to the urea treatments only this year. On 19 February 1994, two adjacent 0.5 m lengths of row were marked using white pot labels at four positions per plot in blocks 1, 2 and 3, and the number of plants counted. The marked rows were located along the north and south edges of each plot, four rows in from the edge as in 1993. The number of live shoots in the marked lengths of row were counted at fortnightly intervals from mid April to mid June. A shoot was classed as dead when the tip of the shoot had died.

Anthesis Growth Analysis

Growth analysis was limited to a single analysis of all treatments at anthesis this year, with the analysis extended to individual leaves in the canopy. Block 2 and 3 were sampled on the 13 June and block 4 was sampled on the 14 June. Details of the sampling procedure were as for year 2. A 25% sub-sample (by fresh weight) was used for analysis. The sub-sample was separated into individual live leaves 1 - 6 down the stem (flag leaf = 1), live stem (leaf sheath + stem) and dead material. Green area of the live components was determined using a leaf area meter (Delta-T Devices, Cambridge). The dry weight of the sub-sample components was determined by drying at 80 ^{0}C for 48 hours.

Intercepted Radiation

Two tube solarimeters (Delta-T Devices, Cambridge), one supported approximately 0.5 m above the top of the canopy and the other placed between the plants along the direction of the rows at the base of the crop, were used to measure radiation above and below the canopy (Plate 6 and 7). Radiation intercepted by the canopy was determined by difference and


Plate 6


Plate 7

Plate 6 and 7 Apparatus used to measure intercepted radiation expressed as a percentage of the incident radiation. Readings were taken at 2 positions per plot. Readings for blocks 1, 2 and 3 were taken on the 15 June and for block 4 on the 16 June.

Harvest growth Analysis

On 9 August, plants were removed at soil level from two adjacent 0.5 m lengths of row at four positions per plot and the samples bulked. The bulk sample from each plot was separated randomly by eye in to 2 x 20 whole plant stems, to be used to determine above ground plant N and C/N ratio of incorporated straw + chaff respectively, and the residual. Ears were cut by hand from all plant stems and ears/m^2 calculated .

Grain was removed from the ears and cleaned using a single ear thresher and grain cleaner as detailed for preparation of the C/N ratio determination sample in years 1 and 2 and the chaff recombined with the straw from the corresponding sub-sample. All plant fractions were dried at 80^{0}C for 48 hours and above ground dry matter calculated by summing dry weights of each fraction and using row width to determine sampling area.

The number of grains in each sub-sample was counted using a grain counter (Henry Simon Ltd., Stockport). Grains per ear were calculated by dividing the total number of grains from each sample by the sample ear number. Thousand grain weight (TGW) of the hand harvested sample was determined from the sample grain number and grain dry weight. Grain from the above ground N sub-sample was recombined with the corresponding straw + chaff fraction to give a whole plant sample for subsequent N analysis.

Above Ground Plant N and C/N Ratio of Incorporated Straw + Chaff

Above ground plant N content and the C/N ratio of the straw and chaff returned to the plots was determined by analysis of the two sub-samples of 20 randomly selected whole plant stems with and without grain respectively. Details of the analysis were as given for the main experiment 1992. Apparent recovery of fertiliser N in the above ground plant dry matter was calculated for each plot.

Grain Yield

The plots were combine harvested on 14 August 1994 using a plot combine and yield adjusted to 85% dry matter.

TGW Combine Sample

A sub-sample of not less than 40 g was obtained from the combine sample from each plot by repeated splitting with a riffler divider and the sub-sample cleaned by passing over a grain cleaner. The fresh weight of the sub-sample was recorded and the grains counted using a grain counter, moisture content of the grain was determined on a ground sample at the time of counting using a moisture meter (Protimeter Ltd., Marlow). TGW was calculated and adjusted to 14% moisture content.

Grain Nitrogen

Grain N was estimated from grain protein determined from the combine sample as in 1992.

Soil Water Nitrate Concentrations in the Subsequent Winter

Following harvest, straw was chopped and spread prior to incorporation. The above ground portion of the tubes from the ceramic suction cups were buried at 30 cm along with a magnet. After ploughing to 20 cm and pressing the following wheat crop was drilled on 23 September 1994 and the plots recovered by triangulation. The buried tubes were relocated with the aid of a magnet detector, recovered to the surface and the holes backfilled. Two neutron probe tubes were inserted to 90 cm adjacent to blocks 1 and 4. Neutron probe readings (Didcot Instruments Ltd., Institute of Hydrology), at 10 cm intervals to 90 cm taken approximately every 2 weeks from the 13/10/94, were used to indicate soil moisture status. The suction cups were sampled at approximately fortnightly intervals over winter from the time of installation to mid March 1995. Details of sampling procedures were as for previous years. Approximately half of the leachate samples were analysed by ion exchange chromatography at HAAC as detailed previously. The remainder of the samples were analysed by ADAS using a colorimetric method (US Geological Survey, 1970; US Environmental Protection Agency, 1973). From the neutron probe data together with MORECS data for the site (Thompson *et al.*, 1981) the return to field capacity was taken as 6/12/95. Nitrate leached was calculated from average soil water nitrate concentration on each sample date and cumulative drainage between sample dates as given by MORECS data for the site .

Soil Mineral N

Soil samples were taken using a set of semi cylindrical gouge augers in the autumn, on the 29 October 1994 after drilling the following crop and in the following spring, on 10 March 1995 prior to the early nitrogen application. Sampling and analytical procedures were as detailed for previous years.

N in Rainfall

A rainfall sample was collected at the site each week from 18/3/94 to 13/3/95 using the apparatus as shown in Plate 4. Location of the sample bottle below ground helped to prevent loss by evaporation. Particulate matter was excluded using a piece of muslin across the funnel top. The sample bottle was emptied weekly and a 20 ml sub-sample collected and analysed for NH_4^+-N and NO_3^--N. Analysis was carried out by ADAS using a colorimetric method (NH_4^+-N: Anon, 1981; NO_3^--N: US Geological Survey, 1970; US Environmental Protection Agency, 1973). Wet deposition of NH_4^+-N and NO_3^--N at the site was calculated from NH_4^+ and NO_3^- concentration in each sample and weekly rainfall as given by MORECS data for the site.

Plate 8

Plate 9

Plate 8 and 9 Apparatus used to sample rainfall at the site

Statistical Methods

Statistical methods were as detailed for years 1 and 2. Skeleton analyses of variance were as shown in Table 3.24. All significant results are quoted at the 5% level.

Table 3.24 Skeleton analysis of variance for the main experiment 1994

Source of Variation	Degrees of Freedom	
	Apparent N recovery	All other analyses
Blocks	3	3
Zero-N v mean of N treatments	-	1
Ammonium nitrate v mean of urea treatments	1	1
Linear foliar urea	1	1
Quadratic foliar urea	1	1
Cubic foliar urea	1	1
Quartic foliar urea	1	1
Deviations	1	1
Residual	18	21
Total	27	31

3.3.3 Results

Weather (Figures 3.10 and 3.11)

The 1994 growing season was hot and dry, characterised by above average temperatures and below average rainfall; the 1994/95 winter was warm and wet, with above average temperatures and particularly high rainfall.

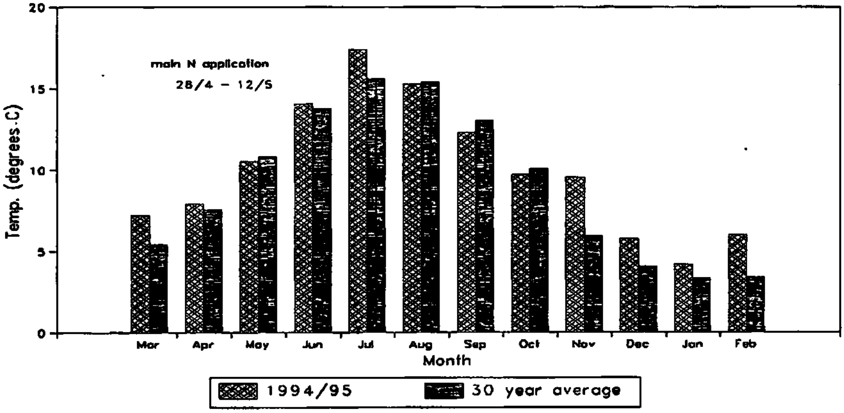


Figure 3.10 Comparison between mean monthly temperatures March 1994 to February 1995 and the 30 year mean (1961-1990)

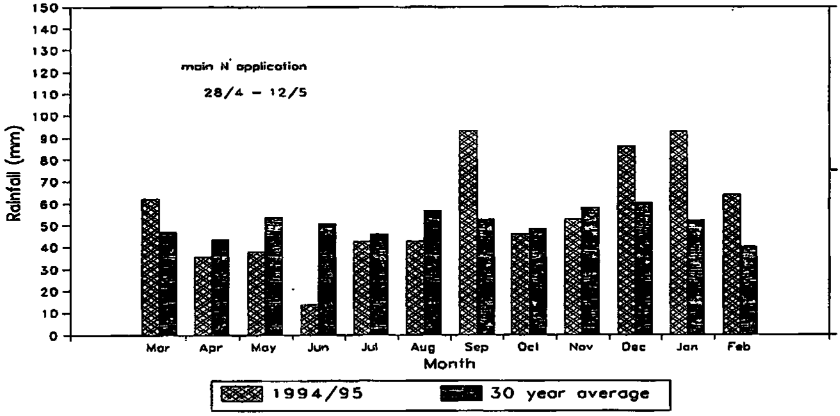


Figure 3.11 Comparison between mean monthly rainfall March 1994 to February 1995 and the 30 year mean (1961-1990)

Grain Yield (Table 3.25)

On average N treatment significantly increased grain yield compared to the zero N treatment. Yield for N applied as ammonium nitrate (6.4 t/ha) was not significantly different to the mean yield for the urea treatments (6.29 t/ha). Within the urea treatment, yield increased to 30 kg N/ha as foliar urea and then decreased slightly to 90 kg N/ha. Yield then increased for 120 kg N/ha as foliar urea before declining again for the all foliar urea treatment. This quartic trend was significant.

Above ground dry matter production (Table 3.25)

On average, N significantly increased above ground dry matter production. Above ground dry matter production for the ammonium nitrate treatment (10.2 t/ha) and urea treatments on average (9.8 t/ha), was not significantly different.

As the rate of N applied as foliar urea increased above ground dry matter showed a significant quartic trend: above ground dry matter production increased up to 60 kg N/ha as foliar urea, decreased for 90 kg N/ha, before increasing and decreasing again for 120 and 170 kg N/ha respectively.

Harvest Index (Table 3.25)

On average N significantly increased harvest index compared to the zero N treatment. There was no significant difference in harvest index between the ammonium nitrate treatment (0.627) and the urea treatments on average (0.647), and within the urea treatments there was no significant trend in harvest index as the rate of N applied as foliar urea increased.

Table 3.25 Grain yield, above ground dry matter production and harvest index in the main experiment 1994

Treatment	Grain yield (t/ha)	Above ground dry matter (t/ha)	Harvest index
Zero N	0.93	3.04	0.278
Ammonium nitrate	6.43	10.25	0.627
Solid urea	5.94	9.84	0.609
30 kg N/ha foliar urea	6.45	10.20	0.635
60 kg N/ha foliar urea	6.28	10.36	0.612
90 kg N/ha foliar urea	6.26	8.99	0.703
120 kg N/ha foliar urea	7.41	11.08	0.672
170 kg N/ha foliar urea	5.39	8.33	0.652
S.E.M.	0.229	0.555	0.0315
C.V. (%)	8.1	12.3	10.5

Shoot Production (Table 3.26)

With the exception of the all foliar urea treatment, maximum shoot production occurred for all treatments in the last week of April. Maximum shoot production for the all foliar urea treatment occurred earlier, the highest recorded shoots/m^2 occurred at the first recording on 15/4/94.

On all sample dates except the last, shoot production showed a similar trend as the rate of N applied as foliar urea increased: shoots/m^2 increased for 30 kg N/ha as foliar urea and then decreased up to 90 kg N/ha as foliar urea. Shoots/m^2 then increased and decreased again for

120 and 170 kg N/ha as foliar urea respectively. The quartic trend in shoot production as the rate of N applied as foliar urea increased was significant on the first three sample dates and was close to significance on the fourth sample date. At the last sample date on 12/6/94, around anthesis, there was no significant trend in shoots/m^2 with increasing rate of N applied as foliar urea.

Table 3.26 Live shoots/m^2 in the main experiment 1994

Treatment	Shoots/m^2				
	April 15	April 28	May 13	May 29	June 12
Solid urea	1308	1352	1204	831	500
30 kg N/ha foliar urea	1462	1500	1350	860	510
60 kg N/ha foliar urea	1323	1420	1313	850	495
90 kg N/ha foliar urea	1345	1397	1276	870	487
120 kg N/ha foliar urea	1536	1560	1464	951	522
170 kg N/ha foliar urea	892	810	757	622	488
S.E.M.	76.1	70.7	70.7	35.3	25.5
C.V. (%)	10	9.1	10	7.4	8.8

<u>Anthesis Growth Analysis</u>

<u>Dry matter production</u> (Table 3.27)

Compared to the zero N treatment, N on average, significantly increased total above ground dry matter, stem dry matter, ear dry matter and dry matter of all leaves at anthesis.

Table 3.27 Dry matter production at anthesis in the main experiment 1994

Treatment	Dry matter (t/ha)									
	Stem	Leaf						Ear	Dead	Total
		1 (flag)	2	3	4	5	total			
Zero N	1.515	0.110	0.142	0.111	0.034	0	0.397	0.015	0.223	2.15
Ammonium nitrate	5.446	0.393	0.446	0.312	0.188	0.036	1.374	0.397	0.440	7.66
Solid urea	5.611	0.404	0.465	0.328	0.225	0.052	1.475	0.330	0.357	7.77
30 kg N/ha foliar urea	6.241	0.439	0.523	0.370	0.239	0.024	1.596	0.295	0.434	8.57
60 kg N/ha foliar urea	5.848	0.412	0.474	0.347	0.236	0.049	1.520	0.256	0.314	7.94
90 kg N/ha foliar urea	5.865	0.421	0.483	0.350	0.227	0.052	1.533	0.445	0.415	8.26
120 kg N/ha foliar urea	6.080	0.428	0.501	0.365	0.250	0.062	1.606	0.506	0.392	8.58
170 kg N/ha foliar urea	4.295	0.422	0.411	0.234	0.145	0.040	1.252	0.146	0.137	5.83
S.E.M.	0.2674	0.0143	0.0192	0.0166	0.0140	0.0091	0.0626	0.0745	0.0380	0.384
C.V. (%)	9.1	6.6	7.7	9.5	12.6	40.2	8.1	43.2	19.4	9.4

Total above ground dry matter, stem dry matter, ear dry matter and total leaf dry matter was not significantly different for the ammonium nitrate treatment and the urea treatments on average. Dry weight of the fourth leaf down the stem (flag leaf = 1) was significantly lower for ammonium nitrate compared to the urea treatments on average. Dry weight of other leaves was not significantly different and this compensated for lower dry weight of the fourth leaf in the total leaf dry weight.

Within the urea treatments, total above ground dry matter at anthesis showed a significant quadratic trend as the rate of N applied as foliar urea increased: dry matter production increased up to 120 kg N/ha as foliar urea and then decreased for 170 kg N/ha as foliar urea. The 30 kg N/ha urea treatment appeared to deviate from this trend, however, this was not significant.

Stem and total leaf dry matter production showed a similar significant quadratic trend as for total dry matter as the rate of N applied as foliar urea increased. As with total dry matter, the 30 kg N/ha foliar urea treatment appeared to deviate from this but this was not significant. With respect to individual leaf dry weight: there was no significant trend in flag leaf dry matter as the rate of N applied as foliar urea increased. Dry weight of leaf 2 and 3 showed a significant quartic trend; increasing for 30 kg N/ha, decreasing for 60 kg N/ha, then increasing again up to 90 kg N/ha as foliar urea before decreasing for 170 kg N/ha. Dry weight of leaf 4 showed a significant quadratic trend, increasing to 120 kg N/ha and then decreasing for 170 kg N/ha as foliar urea, and dry weight of leaf 5 showed a significant cubic trend as the rate of N applied as foliar urea increased, dry weight decreasing for 30 kg N/ha, then increasing up to 120 kg N/ha before decreasing again for 170 kg N/ha.

Ear dry matter showed a significant cubic trend as the rate of N applied as foliar urea increased, decreasing up to 60 kg N/ha foliar urea, then increasing up to 120 kg N/ha foliar urea before decreasing again for 170 kg N/ha foliar urea.

Green Area (Table 3.28)

Compared to the zero N treatment, N on average, significantly increased the total green area index, stem area index, ear area index and leaf area index of all leaves at anthesis. There was no significant difference between the ammonium nitrate treatment and the mean of the urea treatments in total green area index or any of its components at anthesis.

Within the urea treatments, as the rate of N applied as foliar urea increased, total green area index showed a significant quartic trend: green area index increased for 30 kg N/ha, then decreased to 90 kg N/ha, and then increased and decreased again for 120 and 170 kg N/ha as foliar urea respectively. Stem area index displayed a significant quadratic trend, increasing up to 120 kg N/ha and then decreasing for 170 kg N/ha as foliar urea.

Ear area index decreased up to 60 kg N/ha, then increased up to 120 kg N/ha and then decreased again for 170 kg N/ha applied as foliar urea. This cubic trend was significant.

Total leaf area index showed a significant quartic trend within the foliar urea treatments as the rate of N applied as foliar urea increased: leaf area index increased for 30 kg N/ha as foliar urea, decreased to 90 kg N/ha and then increased and decreased again for 120 and 170 kg N/ha as foliar urea respectively. With respect to individual leaves, there was no significant trend in leaf area index of the flag leaf as the rate of N applied as foliar urea. Leaf area index of the

Table 3.28 Green area at anthesis in the main experiment 1994

Treatment	Green area index								
	Stem	Leaf						Ear	Total
		1 (flag)	2	3	4	5	total		
Zero N	0.181	0.163	0.229	0.180	0.045	0	0.617	0.001	0.800
Ammonium nitrate	0.792	0.714	0.857	0.660	0.409	0.065	2.705	0.075	3.572
Solid urea	0.843	0.717	0.861	0.660	0.456	0.095	2.790	0.067	3.700
30 kg N/ha foliar urea	0.952	0.803	1.041	0.788	0.535	0.053	3.219	0.063	4.234
60 kg N/ha foliar urea	0.928	0.778	0.914	0.731	0.498	0.090	3.010	0.052	3.991
90 kg N/ha foliar urea	0.885	0.741	0.914	0.707	0.464	0.080	2.906	0.080	3.872
120 kg N/ha foliar urea	0.952	0.780	0.962	0.761	0.535	0.120	3.158	0.096	4.207
170 kg N/ha foliar urea	0.643	0.771	0.828	0.509	0.308	0.064	2.481	0.027	3.151
S.E.M.	0.0523	0.0313	0.0395	0.0390	0.0387	0.0200	0.1471	0.0139	0.2050
C.V. (%)	11.7	7.9	8.3	10.8	16.5	48.8	9.8	41.8	10.3

second, third and fourth leaves down the stem showed the same significant quartic trend as for total leaf area index. Leaf area index of the fifth leaf showed a significant cubic trend as the rate of N applied as foliar urea increased: leaf area index decreased for 30 kg N/ha as foliar urea, then increased up to 120 kg N/ha before decreasing again for 170 kg N/ha as foliar urea.

Intercepted Radiation (Table 3.29)

N, on average, significantly increased light interception by the canopy compared to the zero N treatments. Light interception was not significantly different between the ammonium nitrate treatment and the urea treatment on average. Within the urea treatments as the rate of N applied as foliar urea increased, light interception by the canopy increased for 30 kg N/ha as foliar urea, decreased up to 90 kg N/ha, before increasing and decreasing again for 120 and 170 kg N/ha as foliar urea. This quartic trend was significant.

Table 3.29 Intercepted radiation at anthesis in the main experiment 1994

Treatment	Intercepted radiation (%)
Zero N	39.81
Ammonium nitrate	72.02
Solid urea	70.46
30 kg N/ha foliar urea	76.16
60 kg N/ha foliar urea	73.34
90 kg N/ha foliar urea	72.37
120 kg N/ha foliar urea	75.25
170 kg N/ha foliar urea	67.2
S.E.M.	1.657
C.V. (%)	4.9

Harvest Growth Analysis (Table 3.30)

N on average, significantly increased ears/m², grains/ear and thousand grain weight (TGW) compared to the zero N treatment.

There was no significant difference in ears/m², grains/ear or TGW for the hand harvested sample between the ammonium nitrate treatment and the urea treatments on average. TGW for the combine sample was significantly lower for the ammonium nitrate treatment compared to the urea treatments on average.

Within the urea treatments there was no significant trend in ears/m² as the rate of N applied as foliar urea increased. Grains/ear showed a significant cubic trend as the rate of N applied as foliar urea increased: grains/ear decreased for 30 kg N/ha as foliar urea, then increased up to 120 kg N/ha before decreasing again for 170 kg N/ha as foliar urea. There was no significant trend in TGW for the hand harvested sample as the rate of N applied as foliar urea increased, however, TGW for the combine sample showed a significant quadratic trend, increasing up to 120 kg N/ha as foliar urea and then decreasing for 170 kg N/ha as foliar urea.

Table 3.30 Harvest growth analysis in the main experiment 1994

Treatment	Ears/m^2	Grains/ear	Thousand grain weight (g)	
			hand sample	combine sample
Zero N	263.1	24.44	33.72	39.51
Ammonium nitrate	437	35.94	45.21	43.97
Solid urea	423.4	38.44	42.81	45.45
30 kg N/ha foliar urea	450.6	35.15	46.5	45.83
60 kg N/ha foliar urea	441.5	36.66	46.07	46.11
90 kg N/ha foliar urea	432.5	36.99	43.71	46.50
120 kg N/ha foliar urea	460.2	38.53	43.98	46.40
170 kg N/ha foliar urea	413.8	34.86	42.01	43.36
S.E.M.	17.14	1.477	1.637	0.481
C.V. (%)	8.3	8.4	7.6	2.2

<u>Above Ground Plant N (kg/ha in the dry matter) & N content (%)</u> (Table 3.31)

N treatment on average, significantly increased N content of the dry matter and above ground plant N compared to the zero N treatment. Above ground plant N was not significantly different between the ammonium nitrate treatment and the urea treatments on average. Within the urea treatments, as the rate of N applied as foliar urea increased, above ground plant N showed a significant quartic trend; increasing for 30 kg N/ha, then decreasing to 90 kg N/ha, before increasing and decreasing again for 120 and 170 kg N/ha as foliar urea. The trend in above ground plant N reflects the trend in above ground dry matter production, differences in N content of the dry matter between urea treatments were small and no trend was significant.

Grain N Concentration (Table 3.31)

N treatment on average, significantly increased grain N concentration and ammonium nitrate significantly increased grain N concentration compared to the urea treatments on average. Within the urea treatments, as the rate of N applied as foliar urea increased, grain N concentration showed a significant linear decrease.

Apparent N Recovery (Table 3.31)

Apparent recovery of fertiliser N applied as ammonium nitrate was not significantly different to the urea treatments on average. Within the urea treatments as the rate of N applied as foliar urea increased, apparent N recovery followed the same quartic trend as for above ground plant N. This trend was significant.

Table 3.31 Above ground plant N and apparent N recovery in the main experiment 1994

Treatment	Above ground plant N		Grain N	Above ground apparent N recovery
	%	kg N/ha	(%)	(%)
Zero N	0.796	24.5	1.611	-
Ammonium nitrate	1.256	129.0	1.994	62.3
Solid urea	1.219	119.7	1.940	56.9
30 kg N/ha foliar urea	1.281	130.1	1.930	63.0
60 kg N/ha foliar urea	1.229	127.4	1.905	61.5
90 kg N/ha foliar urea	1.198	104.7	1.901	48.2
120 kg N/ha foliar urea	1.245	137.1	1.907	67.1
170 kg N/ha foliar urea	1.194	99.7	1.785	45.1
S.E.M.	0.0471	7.76	0.0306	4.82
C.V. (%)	8.0	14.2	3.3	16.7

Soil Mineral N (Table 3.32)

In the autumn, total soil mineral N to 90 cm and in each of the horizons sampled was not significantly different for the zero N treatment and the N treatments on average.

Total mineral N to 90 cm was not significantly different for the ammonium nitrate treatment and the urea treatments on average. Mineral N in the 60-90 cm horizon was significantly higher for ammonium nitrate compared to the urea treatments on average, however, mineral N in the other horizons was not significantly different and compensated for the difference in the 60-90 cm horizon in the total mineral N to 90 cm.

Within the urea treatments, there was no significant trend in total mineral N to 90 cm as the rate of N applied as foliar urea increased. Mineral N in the 60-90 cm horizon showed a significant linear decrease as the rate of N applied as foliar urea increased, however, there was no significant trend in the other horizons and this compensated for the trend in the 60-90 cm horizon in the total mineral N to 90 cm.

In the following spring total soil mineral N to 90 cm and mineral N in each of the horizons was not significantly different for the zero N treatment and the nitrogen treatments on average or for the ammonium nitrate and the urea treatments on average. Within the urea treatments there was no significant trend in soil mineral N.

Table 3.32 Soil mineral N to 90 cm in the main experiment in autumn 1994 and spring 1995

Treatment	Soil mineral N (kg /ha)									
	Autumn					Spring				
	0-15 cm	15-30 cm	30-60 cm	60-90 cm	Total	0-15 cm	15-30 cm	30-60 cm	60-90 cm	Total
Zero N	9.3	9.4	10.9	11.7	41.2	6.0	5.5	4.8	3.5	19.8
Ammonium nitrate	9.9	9.0	16.5	19.7	55.2	5.0	5.5	2.5	3.5	16.5
Solid urea	8.6	9.3	14.7	17.1	49.7	5.8	5.9	5.5	4.1	21.3
30 kg N/ha foliar urea	9.8	9.9	14.2	16.3	50.2	6.2	5.6	4.6	4.4	20.8
60 kg N/ha foliar urea	9.1	10.4	13.5	14.8	47.5	5.3	5.0	3.9	4.8	19.0
90 kg N/ha foliar urea	9.1	9.5	11.5	13.4	43.5	5.7	5.2	4.4	3.8	19.1
120 kg N/ha foliar urea	10.0	10.4	14.1	13.3	47.9	5.6	4.8	3.4	3.0	16.8
170 kg N/ha foliar urea	9.0	10.5	13.2	12.4	45.0	6.1	4.6	2.7	3.7	17.2
S.E.M.	0.82	0.67	1.41	1.79	3.83	0.72	0.49	1.25	1.06	2.92
C.V. (%)	17.6	13.8	20.8	24.1	16.1	25.2	18.7	62.9	54.9	31.0

<u>C/N Ratio of Incorporated Straw + Chaff</u> (Table 3.33)

N, on average, significantly reduced the C/N ratio of incorporated straw + chaff. C/N ratio of straw + chaff for the ammonium nitrate treatment was not significantly different to the urea treatments on average, and within the urea treatments there was no significant trend in the C/N ratio as the rate of N applied as foliar urea increased.

Table 3.33 C/N ratio of incorporated straw + chaff in the main experiment 1994

Treatment	C/N ratio of straw + chaff
Zero N	153.2
Ammonium nitrate	113.8
Solid urea	118.5
30 kg N/ha foliar urea	120.7
60 kg N/ha foliar urea	123.7
90 kg N/ha foliar urea	124.3
120 kg N/ha foliar urea	127.0
170 kg N/ha foliar urea	123.8
S.E.M.	7.19
C.V. (%)	11.4

Nitrate Leaching in the subsequent winter

Figure 3.12 and 3.13 show the nitrate concentration in the soil water at 1 m for each treatment over the subsequent winter. Peak nitrate concentration in the drainage water occurred in late November / early December for all treatments.

As noted earlier, neutron probe data for the site and site specific MORECS data indicated that the site returned to field capacity on 6/12/94. Figure 3.13, however, shows that the nitrate concentration of the soil water at 1 m rose sharply for all plots over the period 29/10/94 - 5/12/94. This increase is typical of a nitrate "front" moving downwards through the profile over this period and indicates therefore, that the actual start of drainage may have been earlier than that estimated by MORECS and neutron probe data. Alternatively, local mineralisation in the vicinity of the cups would produce the same effect in the absence of drainage. The mild November (Figure 3.10) would have been conducive to mineralisation.

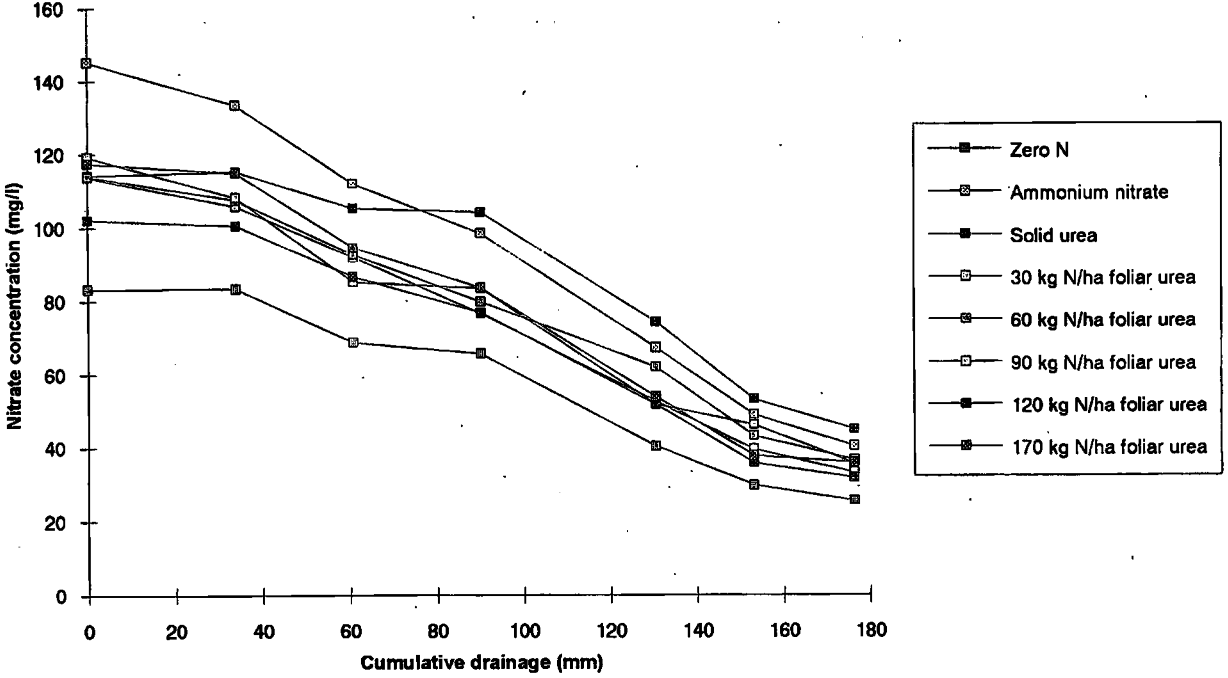


Figure 3.12 Soil water nitrate concentrations with cumulative drainage* over winter 1994/95 for 170 kg N/ha applied as ammonium nitrate and as different proportions of foliar urea in the main experiment (*assumes drainage starts on 6/12/94)

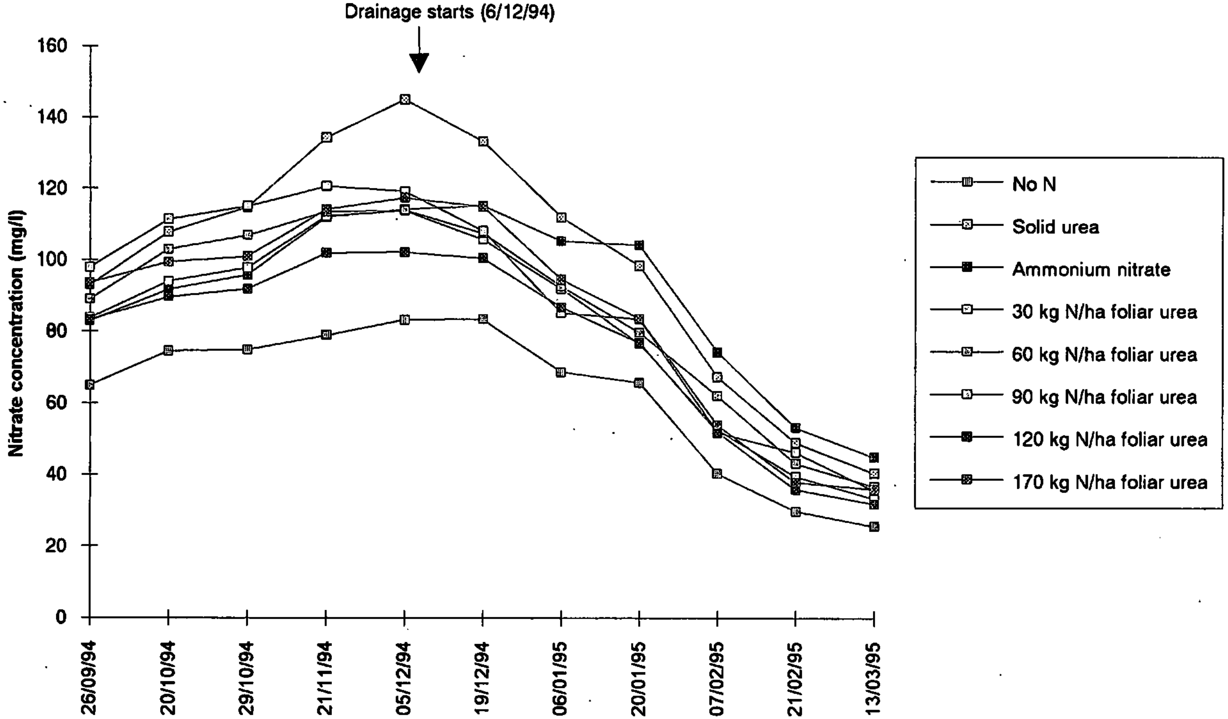


Figure 3.13 Soil water nitrate concentrations with time over winter 1994/95 for 170 kg N/ha applied as ammonium nitrate and as different proportions of foliar urea in the main experiment

Table 3.34 shows the mean soil water nitrate concentration and quantity of nitrate-N leached over the subsequent winter assuming drainage started on 6/12/94 as indicated from MORECS and Neutron probe data, or on 25/10/94 as indicated by inspection from Figure 3.13. While the magnitude of differences between treatments varies according to which date is taken as the start of drainage, trends across the treatments are the same for both data sets. The application of nitrogen fertiliser on average, significantly increased mean nitrate concentration in the soil water and estimated quantity of nitrate-N leached, and mean soil water nitrate concentration and quantity of nitrate-N leached was significantly higher for the ammonium nitrate treatment compared to the urea treatments on average. Within the urea treatments as the rate of N applied as foliar urea increased, there was no significant trend in nitrate concentration or quantity of nitrate-N leached.

<u>N in Rainfall</u> (Table 3.35)

The quantity of NO_3^--N and NH_4^+-N recorded in rainfall at the site over the period 14/3/94 to 13/3/95 is shown in Table 3.35. Wet deposition over this period would have potentially contributed to nitrate leaching over the 1994/95 winter. Nitrogen in rainfall was predominantly in the ammonium form and total annual wet deposition recorded at the site was some 10 kg N/ha.

Table 3.34 Mean soil water nitrate concentration and nitrate-N leached in the drainage water over winter 1994/95 in the main experiment, for drainage starting on 6/12/94 or on the 25/10/94

Treatment	Drainage starts 6/12/94		Drainage starts 25/10/94	
	Mean nitrate concentration in soil water (mg/l)	Nitrate-N leached (kg/ha)	Mean nitrate concentration in soil water (mg/l)	Nitrate-N leached (kg/ha)
Zero N	62.0	24.7	66.5	36.9
Ammonium nitrate	98.7	39.3	106.8	59.4
Solid urea	94.8	37.7	97.6	54.3
30 kg N/ha foliar urea	78.1	31.1	85.9	47.8
60 kg N/ha foliar urea	81.2	32.3	89.5	49.7
90 kg N/ha foliar urea	81.5	32.4	91.8	51.0
120 kg N/ha foliar urea	74.9	29.8	81.2	45.1
170 kg N/ha foliar urea	82.8	33.0	90.71	50.1
S.E.M.	6.14	2.44	6.62	3.68
C.V. (%)	15.0	15.0	14.9	14.9

Table 3.35 Nitrogen deposition in rainfall at the Little Pipe Strine site over the period 14/3/94 to 13/3/95

	NO_3^--N	NH_4^+-N	Total
N (kg/ha)	0.9	9.2	10.1

3.3.4 Discussion

Yield, Above Ground Dry Matter and Harvest Index

Mean grain yield for the nitrogen treatments was some 0.5 t/ha below average yield for the area (MAFF, 1995a). This may have been due to water stress related to the hot dry growing season and light soil type, evidence of drought stress was observed for all treatments around anthesis. As in 1993, there was no significant yield difference between the ammonium nitrate treatment and the urea treatments on average. This year, however, there was evidence of reduced yield for the treatment receiving all of its N as foliar urea, as reported by Poulton *et al.* (1990).

Grain yield is a function of above ground dry matter production and harvest index. The quartic trend in grain yield as the rate of N applied as foliar urea increases reflects the trend in above ground dry matter production. Differences in harvest index were limited this year and unable to compensate for differences in above ground dry matter production in final grain yield.

From the 1993 data the hypothesis was developed, that N applied as foliar urea affects yield by influencing both above ground dry matter production and harvest index, and that the balance of the effect on these two components depends on time of application: early application favours above ground dry matter production but has little effect on harvest index, while later application has little effect on above ground dry matter production but increases harvest index. Time of application in relation to crop development this year was very similar to that in 1993, such that even those treatments receiving a relatively large proportion of N as foliar urea received their nitrogen by GS 32/33, much earlier than in 1992. In line with this hypothesis, with the exception of the 90 kg N/ha and all foliar urea treatment, time of application of foliar urea this year as in 1993, favoured above ground dry matter production with only limited effect on harvest index. As in 1993, the effect on above ground dry matter production as the rate of N applied as foliar urea increased can be related to the trend in green area index at anthesis. The reduced above ground dry matter production and green area index at anthesis for the all foliar urea treatment can be related to smaller leaves and stems possibly attributable to reduced foliar interception of the main N application, due to low shoot populations at this time. This is discussed more fully in the next section. The lower above ground dry matter production for the 90 kg N/ha foliar urea treatment was unexpected. Further, the effect is not evident in the above ground dry matter data at anthesis. Leaf area index and light interception, however, were lower for this treatment at anthesis and an effect on post anthesis dry matter production is therefore indicated. The reason for this and the deviation of this treatment from the general trend as the rate of N applied as foliar urea increased, however, is not readily explained.

Growth Analysis Measurements

Anthesis Growth Analysis

The trend in above ground dry matter at harvest as the rate of N applied as foliar urea increases, correlates well with the trend in above ground dry matter at anthesis, though the 90 kg N/ha as foliar urea appears to deviate from this.

In 1993, dry matter production at harvest showed a close correlation to green area index at anthesis and differences in intercepted radiation were implied. This year, above ground dry matter at harvest was again closely correlated with green area index at anthesis and the radiation data showed that differences in green area index were reflected by differences in intercepted radiation.

Green area index is a function of shoots/m^2 and leaf and shoot size. In 1993, N applied as foliar urea had no effect on shoot production or shoot survival and the trend in green area index (and in turn dry matter production) as the rate of N applied as foliar urea increased, was attributed to N applied as foliar urea affecting leaf size.

This year, while there was no significant trend in shoots/m^2 as the rate of N applied as foliar urea increased at anthesis, on all counts up to anthesis shoots/m^2 showed a significant quartic trend as the rate of N applied as foliar urea increased. Notably shoots/m^2 for the all foliar urea treatment were lower than for the other urea treatments. Early N, applied before or during tillering influences shoot population by affecting tiller production (Biscoe, 1979; Langer, 1980; Darwinkel, 1983; Sylvester-Bradley and Scott, 1990). Later N has less effect on shoot numbers, but can maintain shoot population by offsetting tiller death (Gallagher & Biscoe, 1978b; Darwinkel, 1983; Sylvester-Bradley & Scott, 1990). Reduced shoots/m^2 for the all foliar urea treatment can be related to potentially higher losses of N associated with the early 50 kg N/ha applied as foliar urea in early March, reducing tiller production. Crop cover at this time was limited and interception by the foliage could therefore expected to have been low. Data from the interception experiment at the same site (Section 6.3, Table 6.13) indicates that only around 6% of the early "foliar N" application would actually have been intercepted by the foliage. "Foliar N" reaching the soil surface could have been to subject to gaseous loss by denitrification and / or volatilization. Rate of ammonia volatilisation from urea fertiliser, following hydrolysis to NH_4^+, increases with increasing temperature and wind speed; while rate of denitrification increases with temperature (Haynes and Sherlock, 1986). It is likely therefore, that application of the two early foliar urea sprays at GS 22 in the morning, rather than the evening, as was the case for all other foliar urea applications to the main experiment this year, would have been conducive to gaseous losses due to higher temperatures (day vs night temperatures) following application. Wind speeds may also have been expected to be higher during the day following application in the morning, than over night following evening application, again conducive to volatilisation losses.

The growth analysis data and shoot count data indicate that the trend in green area index as the rate of N applied as foliar urea is due to foliar N affecting the size of the green components: the trend in green area index at anthesis is closely correlated with the trend in stem and leaf area index. This supports the 1993 data.

From the 1993 data, it was inferred that the effect of foliar N on leaf area index was due to effects on leaf expansion rather than leaf persistence. Reference to individual leaf data this year shows that the trend in leaf area index and leaf dry weight as the rate of N applied as foliar urea increases, is largely a reflection of differences in leaf area index and leaf dry weight of leaves lower down the stem, notably leaf 3 and 4, differences in dry weight and leaf area index of the flag leaf (leaf 1) and leaf 2 as the rate of N applied as foliar urea increased were limited. Assuming a phyllocron interval of 128 day °C (mean data for Mercia, Riband, Soisson and Tonic; sown late September at 52° latitude (Kirby, 1994)) back calculation from flag leaf emergence on the 2/6/94, shows that the fourth leaf down the stem would have been almost fully emerged at the start of the main foliar N applications, while the third leaf would have been expanding during the time of foliar N application. The implication therefore, is that the effect of foliar N on leaf area index is due to its effect on the rate of expansion of those leaves developing at the time of application.

The reduced green area index and the associated reduced above ground dry matter production for the all foliar urea treatment may have been related to reduced interception at the time of the main N application. Due to the reduced shoots/m^2 at the time of the main N application, interception of spray by the foliage is likely to have been lower for this treatment. From the above, it follows that the consequence of reduced foliar interception would have been to limit the effect on leaf expansion for this treatment. Similar shoot numbers at anthesis for this treatment but a significantly lower stem dry weight, the quadratic decrease in stem dry weight as the rate of N applied as foliar urea increased was significant, indicates smaller stems. Reduced stem growth is therefore also implicated.

Reduced grain yield at harvest for the all foliar urea treatment was reflected in ear size at anthesis, ear dry weight and ear area index were significantly lower for this treatment, indicating "smaller ears". Spikelet numbers/ear were not recorded at anthesis or harvest, however, it is interesting to speculate that the smaller ears may have been due to fewer spikelets/ear. Early N applied around double ridges (GS 21) increases spikelet production (Langer & Liew, 1973; Darwinkel, 1983). Gaseous loss of N, associated with application of the early 50 kg N/ha as foliar urea has already been implicated as a likely reason for reduced shoot population up to anthesis for this treatment. It would also potentially have reduced spikelets per ear.

Harvest Growth Analysis

Shoot counts at anthesis showed no significant differences in shoots/m^2 as the rate of N applied as foliar urea increased. The lack of any significant trend in ears/m^2 at harvest is therefore as expected and supports the shoot count data.

The significant cubic trend in grains/ear as the rate of N applied as foliar urea increased can be related to the trend in ear size, as reflected by the significant cubic and quartic trend in ear dry weight and ear area index respectively at anthesis. Grains/ear are a function of fertile spikelets/ear and fertile florets/spikelet. Reduced spikelets/ear for the all foliar urea treatment, due to N losses associated with the early N application, has already been postulated as a reason for the reduced ear size at anthesis for this treatment.

From the 1993 results, it was suggested that the increase in harvest index for 120 kg N/ha and 170 kg N/ha foliar urea treatments was due to later N applications for these treatments increasing floret survival. There is no indication from the grains/ear data this year that this is the case, grain numbers/ear were similar for the solid urea treatment and 120 kg N/ha foliar urea treatment.

While there was no significant trend in thousand grain weight as the rate of N applied as foliar urea increased for the hand harvested sample, the significant quadratic decrease in thousand grain weight as the rate of N applied as foliar urea increased for the combine sample indicates a significant decrease in thousand grain weight for the all foliar urea treatment. The decrease in grains/ear and thousand grain weight at harvest for the all foliar urea treatment, was not reflected in a significant decrease in harvest index, due to a corresponding decrease in vegetative plant dry matter.

Apparent Nitrogen Recovery

Apparent recovery of fertiliser N in the above ground crop for all treatments was lower than that recorded in previous years for the site, but is in the range reported elsewhere (Bock, 1984).

Within the urea treatments, the significant quartic trend in apparent N recovery as the rate of N applied as foliar urea increased reflects the trend in above ground dry matter production, N content of the dry matter (N%) for the urea treatments was similar.

In 1992, a significant quadratic decrease in apparent N recovery was recorded as the rate of N applied as foliar urea increased. In 1993, no significant trend in apparent N recovery was evident and this was attributed to application of the early and main applications under conditions that would have been less conducive to gaseous losses by volatilization and/or denitrification principally, application of foliar sprays in the evening rather than during the day as was the case in 1992, and application of the main N earlier in cooler conditions. This year, the significant reduction in apparent N recovery associated with the 170 kg N/ha foliar urea treatment is again evident from the data. This treatment received 120 kg N/ha as urea sprays at the same time as the 120 kg N/ha foliar urea treatment. The implication, is that the reduced apparent N recovery for the all foliar urea treatment this year is attributable to N losses associated with the early 50 kg N/ha. This year as in 1992, the early foliar urea sprays were applied to the plots in the morning. As noted previously (p188, this section), warm windy conditions following application of foliar urea early in the day would have been conducive to N losses by volatilisation and / or denitrification, following hydrolysis of urea to NH_4^+. Reduced shoot production up to anthesis for the all foliar urea treatment, associated with reduced uptake of early N by the plants, supports this hypothesis. The early application of 50 kg N/ha, represents almost a third of the total N applied, as such the importance of losses associated with it should not be under estimated.

The reduction in apparent N recovery for the 90 kg N/ha foliar urea treatment appears to be anomalous and is not readily explained. It is a reflection of the lower above ground dry matter at harvest, which as noted earlier was not expected and was not supported by the growth analysis data at anthesis. The 90 kg N/ha foliar urea treatment received foliar sprays at the same time as the 30 and 60 kg N/ha foliar urea treatments and, with the exception of the final spray, the 120 kg N/ha foliar urea treatment (Table 3.23). There is no logical reason why recovery should be lower for this treatment compared to the other urea treatments up to 120 kg N/ha as foliar urea.

The significant linear decrease in grain N concentration as the rate of N applied as foliar urea increased, supports the data for the previous two years.

C/N Ratio of Incorporated Straw + Chaff

Despite the quartic trend in apparent N recovery as the rate of N applied as foliar urea increased, in particular the decrease in apparent N recovery for 170 kg N/ha applied as foliar urea, there was no significant trend in C/N ratio of the straw + chaff. In 1992, the decrease in apparent N recovery for this treatment was reflected in a substantial increase in the C/N ratio of straw + chaff. While the decrease in apparent N recovery this year was less than in 1992, N losses from the early N only being implicated and not further compounded by losses from the main application as was the case in 1992, some evidence of an increase in the C/N ratio of the straw + chaff would have been expected. In fact, from the data a small reduction in the C/N ratio of the straw + chaff for 170 kg N/ha foliar urea treatment is indicated, however, this was not significant.

Soil Mineral N

Soil mineral N values to 90 cm in the autumn were lower than in previous years. This may have been related to reduced mineralization during the late summer and early autumn this year due to very dry soil conditions. MORECS and neutron probe data for the site indicate that the soil did not return to field capacity until the start of December and that the soil was still in deficit (SMD = 60 mm) at the time of sampling on 29/10/94.

The distribution of soil mineral N to 90 cm in the autumn was similar to that recorded in 1993: 40% of the mineral N to 90 cm was in the top soil (0-30 cm), 28% in the 30-60 cm horizon and 31% in the 60-90 cm horizon (mean data for all treatments). Despite the drier soil conditions in September and October this year compared to 1993, the similar distribution of mineral N in the profile may have been related to particularly heavy rainfall on 14/9/94 (42.6 mm) that could be expected to have moved mineral N down the profile as in 1993.

Due to restricted soil mineralisation / immobilisation prior to sampling in the autumn this year, soil mineral N in the autumn would be expected to reflect apparent recovery of fertiliser N in the above ground crop. This was the case for the ammonium nitrate treatment compared to the urea treatments on average, there was no significant difference in apparent N recovery or soil mineral N in the autumn, however, the quartic trend in apparent N recovery within the urea treatments, in particular the low apparent N recovery for the all foliar urea treatment, was not reflected in higher soil mineral N in the autumn.

Soil mineral N to 90 cm in spring 1995 was substantially lower than in previous years. This is a reflection of lower soil mineral N in the autumn as discussed above, together with similar over winter leaching.

Nitrate Leaching

The date at which drainage starts has implications with respect to the average nitrate concentration in the soil water and the quantity of nitrate-N leached over the drainage period. The discrepancy in estimating the start of drainage has a limited effect on the estimate of average nitrate concentration in the drainage water, but a larger effect on the estimate of quantity of nitrate leached. The quantity of nitrate-N leached (average for N treatments) increases by 17 kg N/ha if drainage started in late October compared to early December. Lord and Shepherd (1993) have emphasised the importance of accurately determining the start of drainage in estimating N leaching losses.

The quantity of nitrate-N leached over winter is a function of soil mineral N in the autumn, subsequent mineralisation / immobilisation and cumulative drainage for the period. Nitrate leaching for the treatments over the 1994/95 winter in general reflects the trend in soil mineral N in the autumn for the treatments. The significantly lower nitrate leaching from the zero N plots and the significantly higher nitrate leaching from the ammonium nitrate treatment compared to the urea treatments on average, is therefore as expected given the autumn soil mineral N data. That the differences were not significant with respect to autumn soil mineral N, but are significant with respect to nitrate leaching, may be related to differences in the C/N ratio of the incorporated straw + chaff giving rise to differences in the immobilisation / mineralisation balance in the soil when it wetted up. The significantly higher C/N ratio of the straw and chaff returned to the zero N plots would have favoured immobilisation, while the lower C/N ratio of the straw + chaff returned to the ammonium nitrate plots compared to the urea plots (though not significant), would have been less conducive to immobilisation. The hypothesis that differences in the soil mineralisation / immobilisation balance, due to differences in the C/N ratio of incorporated straw and chaff, was tentatively proposed as a possible explanation for the differences in autumn soil mineral N and/or nitrate leaching between treatments in the first two years of the experiment. While differences in the C/N ratio of straw + chaff between treatments were even more limited this year than in previous years and not significant, the general trend of high C/N ratio associated with lower quantity of N leached further supports this hypothesis.

In comparison with previous years, if the start of drainage is taken as 6/12/94, then nitrate concentration in the drainage water and quantity of nitrate-N leached over winter were the lowest recorded for the site over the 3 years. This is as expected, given the low weight of soil mineral N recorded in the autumn and the moderate over winter drainage this year compared to previous years (176 mm 1994/95, 233 mm 1993/94, 157 mm 1992/93). However, if the start of drainage is taken as the 25/10/94, then the quantity of nitrate-N leached is higher than expected compared to previous years given the cumulative drainage and autumn soil mineral N values. As shown in Table 3.36, quantity of nitrate-N leached over the 1994/95 winter was similar to that leached over the 1993/94 winter, however, while over winter cumulative drainage was the same, soil mineral N in the previous autumn was some 17 kg N/ha less in 1994/95. By calculation, some 13 kg N/ha of the nitrate-N leached over the 1994/95 winter was attributable to increased mineralisation over the 1994/95 winter compared to the 1993/94 winter. The high soil moisture deficit over the summer at the site in 1994, restricting mineralisation prior to the autumn soil sampling, followed by the mild winter in 1994 compared to 1993 support this.

Table 3.36 Comparison of cumulative drainage, soil mineral N in the autumn and N leached over winter for years 2 and 3 of the main experiment

	1993/94	1994/95
Cumulative drainage (mm)	233	233*
Autumn soil mineral N (kg /ha) (average of all N treatments)	65	48
Nitrate-N leached (kg/ha)	55	51

* assumes drainage starts on 25/10/94

The estimated quantity of nitrate-N leached is between 34 kg N/ha and 51 kg N/ha (mean of N treatments), corresponding to cumulative drainage of 176 mm or 233 mm according to whether the site started to drain on the 25/10/94 or 6/12/94 respectively. In both cases, the estimated quantity of N leached is high compared to the range recorded elsewhere of 10 - 51 kg N/ha/year, corresponding to cumulative drainage of 140-330 mm respectively, for sandy soils in continuous cereals (Goulding and Poulton, 1992).

Nitrate concentration in the drainage water is less affected by the date chosen for the start of drainage. Table 3.34 shows that nitrate concentration in the drainage water for the N treatments is between 1.5 to 2 times the EU limit of 50 mg/l (Council of the European Communities, 1980 and 1991). The implication is clear, even in a year when the contribution from mineralisation is limited due to very dry soils, and nitrogen is applied according to recommendations, nitrate concentrations in the drainage water are still in excess of legal limits set. The higher than expected levels of nitrate leaching at the site support the results obtained in the previous two years. Recently Johnson *et al.*(1996), have reported high concentrations of nitrate in the drainage water and high quantities of nitrate-N leached from winter barley plots following winter wheat in an arable rotation, receiving N fertiliser according to standard recommendations. On average over five years, 48 kg N/ha was leached per year, corresponding to a mean nitrate concentration in the drainage water of 119 mg/l and an average annual drainage of 197 mm.

N in Rainfall

Annual wet deposition of N in rainfall as calculated for the Little Pipe Strine site agrees well with data recorded elsewhere. Goulding (1990), has reported an average of 10 kg N/ha as wet deposition recorded at four sites in southern and eastern England. However, in contrast to the data recorded at this site, the proportions of NH_4^+-N and NO_3^--N were surprisingly constant over the four sites, approximately 57% was in the NH_4^+ form and 43% was in the NO_3^- form. The high proportion of N in the NH_4^+ form at this site therefore appears unusual.

Wet deposition only was recorded in this experiment. Dry deposition of N in particulate and gaseous forms as reported by Goulding, averaged some 25 kg N/ha, giving a total annual atmospheric input of some 35 kg N/ha. Nitrogen balances calculated for the Broadbalk experiment at Rothamsted have indicated annual atmospheric inputs of between 38 kg N/ha and 48 kg N/ha (Jenkinson, 1982; Powlson *et al.*, 1986a respectively). All the data therefore indicate an annual deposition to arable land of some 40 kg N/ha. Measurement of N in rainfall at the site was undertaken as an indication of the potential contribution of atmospheric N deposition to nitrate leaching at the site. While dry deposition was not measured, results for wet deposition are in the order reported elsewhere, and indicate no reason to suspect that total atmospheric N inputs at the site are unusually high. It is unlikely therefore, that the high nitrate leaching recorded at this site can be attributed to abnormally high N deposition from the atmosphere.

3.3.5 Summary of Findings for the Main Experiment 1992 - 1994

The results from the main experiment over three years, indicate that N applied as foliar urea can produce similar yields to N applied conventionally to the soil as solid ammonium nitrate or urea. In 1994, there was evidence of a reduction in yield for the treatment receiving all of its N as foliar urea, however, gaseous losses from the early N application around GS 21 were implicated.

Consideration of the harvest data over the three years indicates that foliar urea maintained yield by influencing both above ground dry matter production and harvest index, and that it appeared to be compensatory in these effects; an increase in above ground dry matter production offsetting a decrease in harvest index and *vice versa*, such that yield was maintained. Further, consideration of the data over the three years in relation to time of application of foliar urea, indicated that the balance between the effect on above ground dry matter and harvest index was determined by time of application of foliar urea in relation to stage of plant development: early application of foliar urea increased above ground dry matter production and had little effect on harvest index, while later applications reduced above ground dry matter production and increased harvest index.

The effect of time of application of foliar urea was confounded by the rate of N applied as foliar urea. As the rate of N applied as foliar urea increased, due to the interval between successive sprays, a larger proportion of the total N was applied later. Further work was therefore carried out to separate these factors.

Growth analysis conducted in 1993 and 1994 indicated that the effect of foliar urea on above ground dry matter production at harvest was due to effects on green area index at anthesis influencing intercepted radiation. The results indicate that this effect was due to foliar N affecting the size of green stems and leaves. Further, the data indicate that the effect of foliar urea on leaf area index was due to foliar N affecting the rate of leaf expansion rather than leaf persistence, and there is an indication that this effect is largest for those leaves developing at the time of application.

It is postulated that the effect of later applications of foliar urea on harvest index may be due to foliar N affecting floret death. However, the results of the harvest growth analysis conducted in 1994 were inconclusive in this respect.

All N applications in the main experiment were made at 170 kg N/ha. It is obviously important, that the yield effects recorded for N applied as foliar urea are reproducible over a range of rates of N applied. Further work was therefore carried out to determine yield response to foliar urea at different rates of N applied.

With respect to N losses, in 1992 reduced apparent recovery of fertiliser N in the above ground crop and reduced soil mineral N in the autumn, indicated gaseous losses and / or immobilisation of fertiliser N as the rate of N applied as foliar urea increased. Consideration of differences in apparent N recovery for the foliar urea treatments over the three years in relation to time of application of foliar urea sprays and prevailing weather conditions, indicates that gaseous losses can occur for foliar urea applied under conditions conducive to volatilisation and / or denitrification, and that these can be important at high rates of N applied. Immobilisation of fertiliser N in the soil organic matter, however, cannot be ruled out. Further work, using ^{15}N

labelling techniques was therefore conducted to measure true recovery of fertiliser N in the plant and soil (mineral + organic fractions), to determine whether differences in apparent N recovery in the plant-soil system mineral N system for N applied as foliar urea are due to gaseous losses as implied, or immobilisation of fertiliser N in the soil organic matter.

Differences in autumn soil mineral N and nitrate leaching for N applied as foliar urea, can be related to differences in the C/N ratio of incorporated straw + chaff, associated with the inferred gaseous N losses due to application of foliar urea sprays under conditions conducive to volatilisation and / or denitrification. It was postulated that differences in autumn soil mineral N and nitrate leaching for N applied as foliar urea were due to differences in C/N ratio of the incorporated plant residues influencing the mineralisation / immobilisation balance of soil mineral N in the autumn and early winter. There was an indication from the data, that application of foliar urea under conditions conducive to gaseous losses, associated with a significant decrease in apparent N recovery in the above ground dry matter and a significant increase in the C/N ratio of the incorporated straw and chaff, can potentially reduce nitrate leaching.

A number of the hypotheses proposed from the results of the main experiment implicitly assume that N applied as foliar urea is intercepted by the foliage. Given the limited crop cover at the time of N application, particularly at the time of the early N application around GS 21, interception of "foliar urea" by the foliage may be low. Further work was therefore carried out to determine for N applied as foliar urea, the proportion of N intercepted by the foliage and the proportion intercepted by the soil.

The additional experiments conducted to investigate the areas highlighted for further work were carried out in 1993 and 1994.

4.0 ^{15}N-LABEL EXPERIMENT

In the main experiment carried out in 1992, recovery of fertiliser N in the above ground crop was determined on an apparent basis only. This method places considerable weight on the performance of the control plots, and assumes that immobilisation / mineralisation and other N transformations during the experiment are the same for both untreated and treated soils i.e. that they are unaffected by N application (section 2.2.4 (i)). Further, measurements of soil N in the autumn were restricted to the mineral N fraction and immobilisation of fertiliser was implicated in the lower overall apparent recovery of fertiliser N in the crop-soil mineral N system. Measurement of total soil N i.e. mineral + organic N, would not be sufficiently sensitive to detect differences in immobilisation between treatments. An ^{15}N label experiment was therefore carried out in 1993 within the main experiment, to determine true recovery of fertiliser N in the crop-soil mineral N system (mineral + organic soil N).

4.1 Field Treatments

For selected treatments in the main experiment; solid ammonium nitrate, solid urea, 25% (30 kg N/ha) and 100% (120 kg N/ha) of the main application as foliar urea, ^{15}N labelled 2 x 2 m microplots were established within the main experiment on Little Pipe Strine field. Details of the site and establishment methods were as given for the main experiment 1993. Nitrogen treatments in the spring were as shown in Table 4.1.

Table 4.1 Nitrogen treatments in the ^{15}N label experiment 1993

Trt. Ref.	N in early March (kg N/ha)		N at GS 31 (kg N/ha)		Total N (kg/ha)
	Rate	Form	Rate	Form	
1	0	-	0	-	0
2	50	Solid ammonium nitrate	120	^{15}N labelled solid ammonium nitrate	170
3	50	Solid urea	120	^{15}N labelled solid urea	170
4(a)	50	Solid urea	90	^{15}N labelled solid urea	
			30	Unlabelled foliar urea	170
4(b)	50	Solid urea	90	Unlabelled solid urea	
			30	^{15}N labelled foliar urea	170
7	50	Solid urea	120	^{15}N labelled foliar urea	170

Each treatment was replicated four times within the randomised block design of the main experiment. For the purposes of the ^{15}N experiment, an additional plot was added to each block to accommodate treatment 4(b). The plot layout within the main experiment is shown in Figure 4.1.

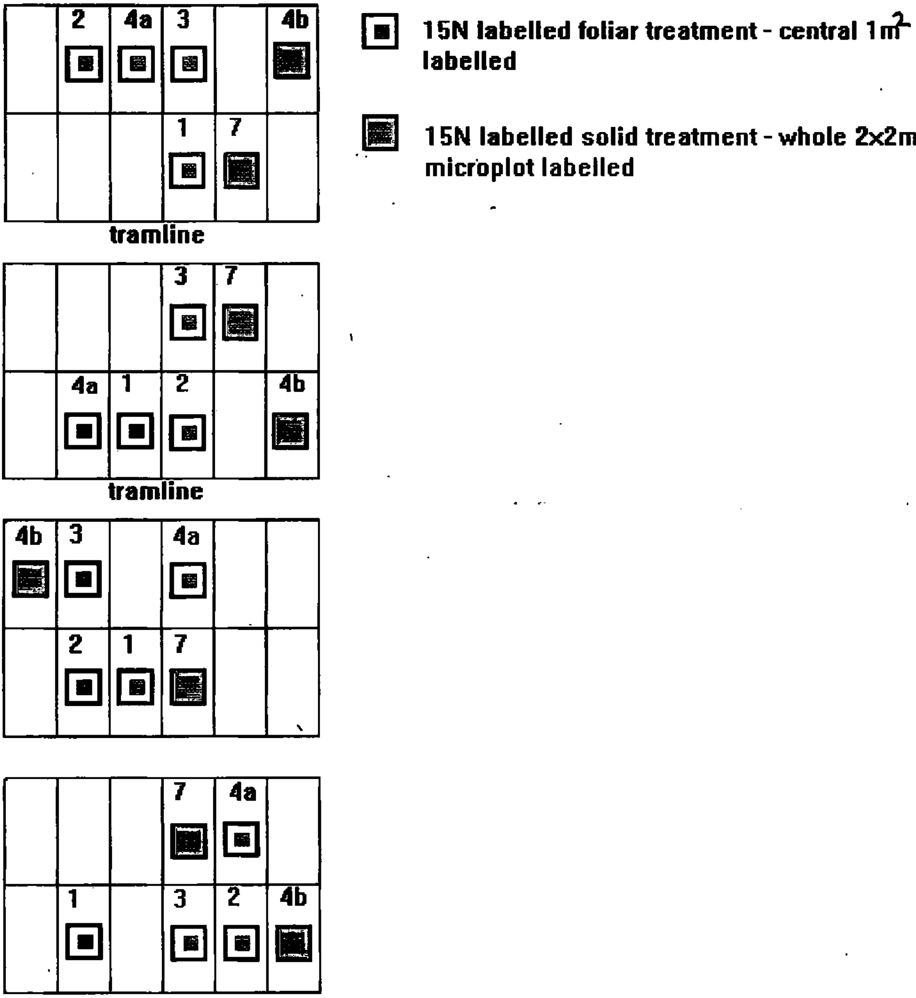


Figure 4.1 Plot layout and randomisation of ^{15}N microplots within the main experiment, showing ^{15}N labelled area (numbers refer to treatments, refer to Table 4.1)

Application of ^{15}N-labelled Fertiliser

For those treatments receiving ^{15}N-labelled solid ammonium nitrate or urea, the 2 x 2 microplots were covered with a plastic sheet mounted on a Dexian frame when the unlabelled N fertiliser was broadcast over the rest of the plot. The covers were then removed and the ^{15}N-labelled fertiliser applied to the whole of each microplot at the appropriate rate. To aid even application, the solid fertiliser was applied to the microplots as a solution (appropriate weight of ^{15}N-labelled product dissolved in 1 l of distilled water) using a watering can fitted with a dribble bar. The solution was applied in two passes at right angles to each other and the volume of any residual solution recorded. Immediately after applying the labelled fertiliser solution, each plot was watered with 2 l of distilled water from a watering can to wash the labelled fertiliser off the wheat plants and on to the soil.

For those treatments receiving ^{15}N-labelled foliar urea, the negative discard method was used as described by Powlson *et al.* (1989a). The central 1 m^2 of each microplot was covered with a plastic sheet mounted on Dexian frame when the unlabelled foliar urea was applied to the rest of the plot. The central area was then uncovered and sprayed with ^{15}N-labelled urea at a rate equivalent to 30 kg N/ha in 300 l using a 550 ml hand held pot sprayer (Hozelock U.K. Ltd.). The spray was applied in two passes at right angles to each other and the exact amount of spray applied determined by weighing the sprayers before and after each application. A right angled windbreak constructed from hessian cloth mounted on a Dexian frame, placed along the windward edges of the microplot was used to minimise drift from the target area. For foliar treatments, as in the main experiment, the objective was to apply 30 kg N/ha every 4 to 5 days, starting at GS 31, to give the required rate of labelled N as foliar urea according to treatment.

Unlabelled solid and foliar N was applied to the microplots at the same time as the applications to the main plot. Details of unlabelled applications were as described for the main experiment. Actual dates and growth stages of N applications are given in Table 4.2.

The ^{15}N enrichment of the labelled ammonium nitrate and urea was nominally 5 atom % excess, atom % excess being defined as measured atom % ^{15}N - 0.3663. Actual enrichment of the fertiliser solutions applied is given in Table 4.2.

Table 4.2 Dates of N applied in the ^{15}N label experiment 1993

		TREATMENT					
		(1)	(2)	(3)	(4a)	(4b)	(7)
Date Applied	ZGS	Zero-N	NH_4NO_3 (kg N/ha)	Solid urea (kg N/ha)	30 kg N/ha Foliar urea (solid labelled) (kg N/ha)	30 kg N/ha Foliar urea (foliar labelled) (kg N/ha)	120 kg N/ha Foliar urea (kg N/ha)
16/3	23		50	50S	50S	50S	50S
19/4	30/31					90S	
20/4	30/31		120 (^{15}N-labelled)(a)	120S (^{15}N-labelled)(b)	90S (^{15}N-labelled)(c)		
22/4	31				30F		
26/4	31					30F (^{15}N-labelled)(d)	30F (^{15}N-labelled)(d)
29/4	31						30F (^{15}N-labelled)(d)
4/5	31/32						30F (^{15}N-labelled)(d)
10/5	33						30F (^{15}N-labelled)(d)
Total		0	170	170	170	170	170

S = Urea applied as solid F = Urea applied as foliar spray

(a) 4.437 at. % excess, (b) 4.421 at. % excess, (c) 4.405 at. % excess, (d) 4.182 at. % excess.

4.2 Sampling and Analytical Techniques

Grain and Straw

For those treatments receiving ^{15}N-labelled solid ammonium nitrate or urea, plants were cut by hand at 5 cm above ground level from the central 1 m^2 of each microplot and all plant material quantitatively collected. For the labelled foliar treatments, plant material was collected from the whole microplot (4 m^2) by cutting at 5 cm above ground level. Microplots were sampled on the 26 to 27 August, immediately prior to combining the main plots.

Stubble

Immediately after harvest on the 30 August, stubble (including crown just below the soil surface) from two adjacent 0.5 m lengths of row at two positions per plot, was collected from the central 1 m^2 of each microplot and adhering soil removed by rinsing carefully under running water.

Soil

Soil samples were taken using a set of semi cylindrical gouge augers immediately after harvest (1 September 1993) from within the central 1 m^2 of each microplot, after removing the stubble. The soil was sampled over four depths; 0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm. As far as possible, care was taken not to disturb the sides of the hole when sampling the deeper horizons, to minimise the risk of sub soil samples being contaminated with the more highly enriched top soil. Five cores were taken per plot and the soil from each horizon bulked. Following collection and transport to the laboratory (approximately 6 hours) samples were stored frozen prior to sieving and drying.

The bulk density of the soil in each of the horizons sampled was determined at the time of sampling, by digging a pit to 1 m adjacent to each block and collecting a soil sample from each horizon and determining the volume sampled by backfilling the sample hole with horticultural grit and recording the volume used. The soil was air dried and sieved through a 6.35 mm sieve. The soil was then oven dried at 105 ^{0}C for 24 hours and the dry weight of soil per hectare in each horizon calculated for each block. Bulk density was measured on a block basis rather than on a plot basis, to avoid affecting the drainage characteristics of the soil with respect to the ceramic suction cup samplers.

Sample Preparation

The ears were separated from the stems and the grain threshed out using a Wintersteiger Single Ear Thresher (F. Walter - H. Wintersteiger, Austria), modified to allow quantitative collection of threshed grain + chaff. The grain was then separated from the chaff by passing the grain + chaff fraction over a grain cleaner (A/S Rationale Kornservice Sample Cleaner) fitted with a 3.5 mm top sieve and a 2 mm bottom sieve, quantitatively collecting grain and chaff separately. Two grain samples (100 g each) were obtained by repeated mixing and quartering of the entire sample using a riffle sample divider.

The straw was chopped into lengths of 5 to 10 cm using a domestic garden shredder (Al-Ko, Germany) modified to facilitate quantitative collection. Straw and chaff were then recombined and mixed for 10 minutes in a clean cement mixer and a representative 70 g sub sample of straw + chaff obtained by repeated mixing and quartering of the entire sample. Throughout the preparation of grain and straw + chaff sub samples, all equipment was dismantled and cleaned between samples to minimise cross contamination by ^{15}N dust.

For N analysis, grain, straw + chaff sub samples and the whole of the stubble sample were dried at 80 ^{0}C for 18 hours. After thawing, soil samples were sieved through a 6.35 mm sieve and dried at 45 ^{0}C overnight to simulate rapid air drying. All samples were then ground in a disk mill (Tema model T100), which was washed between samples to eliminate cross contamination. Total N and $^{15}N/^{14}N$ ratios were determined using a 20-20 stable isotope mass spectrometer fitted with a solid/liquid preparation unit (Europa Scientific, Crewe, Cheshire). Additional samples of grain, straw + chaff, stubble and soil were dried at 105 ^{0}C for 24 hours for dry matter determination at the time of analysis.

Statistical Methods

Results were analysed using the Statgraphics statistical programme. The data was analysed by analysis of variance and the least significant difference method. The skeleton analysis of variance is shown in Table 4.3. All significant results are quoted at the 5% level of significance.

Table 4.3 Skeleton analysis of variance for the ^{15}N label experiment

Source of variation	Degrees of Freedom
Blocks	3
Treatments	4
Residual	12
Total	19

4.3 Results

Crop Yield and N Uptake

Yields and nitrogen uptake by the straw and stubble are given in Table 4.4. As in the main plots, there was no significant difference in grain yield between treatments. Straw yield was significantly higher for the ammonium nitrate compared to the solid urea and all foliar urea treatments, however, this difference was not reflected in total dry matter production.

In contrast to the main plots there was no significant difference in N concentration in the grain between treatments. As in the main plots, there was no significant difference in N uptake by the crop between treatments, reflecting the similar dry matter production and %N. Apparent recovery of fertiliser N in the above ground crop for the ^{15}N microplots was similar to that recorded for the corresponding treatment in the main experiment and differences between treatments were not significant.

Recovery of Labelled N

Recovery of nitrogen ^{15}N-labelled fertiliser in the crop and soil is shown in Table 4.5 and 4.6, Figure 4.2 and 4.3. Application of all of the main spring N as ammonium nitrate, solid urea or as foliar urea had no significant effect on percentage recovery of labelled N in the crop or soil. Percentage recovery of labelled N in the straw and chaff was significantly higher for N applied as ammonium nitrate compared to N applied as solid or foliar urea, however, this difference was not reflected in total recovery in the crop.

Application of a proportion of the total N (30 kg N/ha) as foliar urea had no significant effect on percentage recovery in the crop or soil of labelled N applied as solid urea. Application of only 30 kg N/ha as foliar urea (90 kg N/ha applied as solid urea) compared to all of the N applied as foliar urea significantly reduced percentage recovery of labelled foliar N in the straw and chaff and significantly increased percentage recovery of labelled foliar N in the 15-30 cm horizon in the soil, however, these differences were compensated for by recovery in the other crop and soil fractions and overall application of N as solid urea had no significant effect on total percentage recovery in the crop and soil of labelled N applied as foliar urea.

Table 4.4 Yield and nitrogen uptake in the ^{15}N label experiment 1993

Treatment	Yield (t/ha @ 85% DM)				%N			N uptake (kg/ha)				Apparent N
	Grain	Straw	Stubble	Total	Grain	Straw	Stubble	Grain	Straw	Stubble	Total	Recovery (%)
Ammonium nitrate	9.29	7.72	2.64	19.65	1.85	0.70	0.98	146.1	45.9	21.8	213.8	79.94
Solid urea	9.04	6.97	2.62	18.63	1.75	0.63	0.81	134.3	37.3	17.9	189.6	65.66
30 kg N ha^{-1} Foliar urea (solid labelled)	9.33	7.47	2.79	19.60	1.86	0.64	0.84	146.0	40.6	20.0	206.6	75.15
30 kg N ha^{-1} Foliar urea (foliar labelled)	8.14	6.63	3.37	18.63	1.91	0.62	0.77	131.4	34.7	22.2	188.3	65.83
120 kg N ha^{-1} Foliar urea	9.34	6.98	3.07	19.39	1.82	0.61	0.81	144.3	36.7	21.5	202.5	75.00
L.S.D. (P = 5%)	1.488	0.728	0.576	2.413	0.147	0.071	0.143	24.89	6.95	6.10	30.79	18.210
S.E.M. (P = 5%)	0.483	0.236	0.187	0.783	0.047	0.022	0.047	8.08	2.26	1.98	9.99	5.91
C.V. (%)	10.7	6.6	12.9	8.2	5.2	7.0	11.3	11.5	11.6	19.1	10.0	16.3

Table 4.5 Percentage recovery of ^{15}N-labelled fertiliser in 1993

	Recovery of ^{15}N-labelled fertiliser (%)									
Treatment	Crop				Soil					Total
	Grain	Straw	Stubble	Total	0-15 cm	15-30 cm	30-60 cm	60-90 cm	Total	
Ammonium nitrate	54.02	15.11	5.23	74.36	11.64	1.95	2.56	2.02	18.18	92.54
Solid urea	47.49	12.16	4.06	63.70	13.58	2.31	4.15	2.76	22.81	86.51
30 kg N ha^{-1} Foliar urea (solid labelled)	45.90	11.79	4.37	62.06	13.14	2.66	3.79	3.30	22.89	84.96
30 kg N ha^{-1} Foliar urea (foliar labelled)	39.98	10.05	4.89	54.82	14.51	3.03	2.26	3.35	23.15	77.96
120 kg N ha^{-1} Foliar urea	54.25	12.79	4.43	71.47	10.49	1.79	4.08	3.02	19.38	90.85
L.S.D. (P = 5%)	15.927	2.226	1.098	17.295	7.100	0.894	2.067	1.635	8.040	19.222
S.E.M. (P = 5%)	5.167	0.722	0.356	5.611	2.304	0.290	0.671	0.531	2.608	6.237
C.V. (%)	21.4	11.7	15.5	17.2	36.4	24.7	39.8	36.7	24.5	14.4

Table 4.6 Recovery of ^{15}N-labelled nitrogen in 1993

Treatment	^{15}N labelled nitrogen applied	Recovery of ^{15}N-labelled nitrogen (kg/ha)									
		Crop				Soil					Total
		Grain	Straw	Stubble	Total	0-15 cm	15-30 cm	30-60 cm	60-90 cm	Total	
Ammonium nitrate	121.86	65.83	18.41	6.37	90.61	14.18	2.38	3.12	2.46	22.15	112.77
Solid urea	122.20	58.02	14.86	4.96	77.84	16.59	2.82	5.07	3.37	27.87	105.71
30 kg N ha^{-1} Foliar urea (solid labelled)	93.12	42.74	10.98	4.07	57.79	12.24	2.48	3.53	3.07	21.31	79.11
30 kg N ha^{-1} Foliar urea (foliar labelled)	29.81	11.89	3.00	1.45	16.34	4.32	0.90	0.67	1.00	6.90	23.24
120 kg N ha^{-1} Foliar urea	117.82	63.92	15.07	5.22	84.21	12.36	2.11	4.81	3.56	22.83	107.04

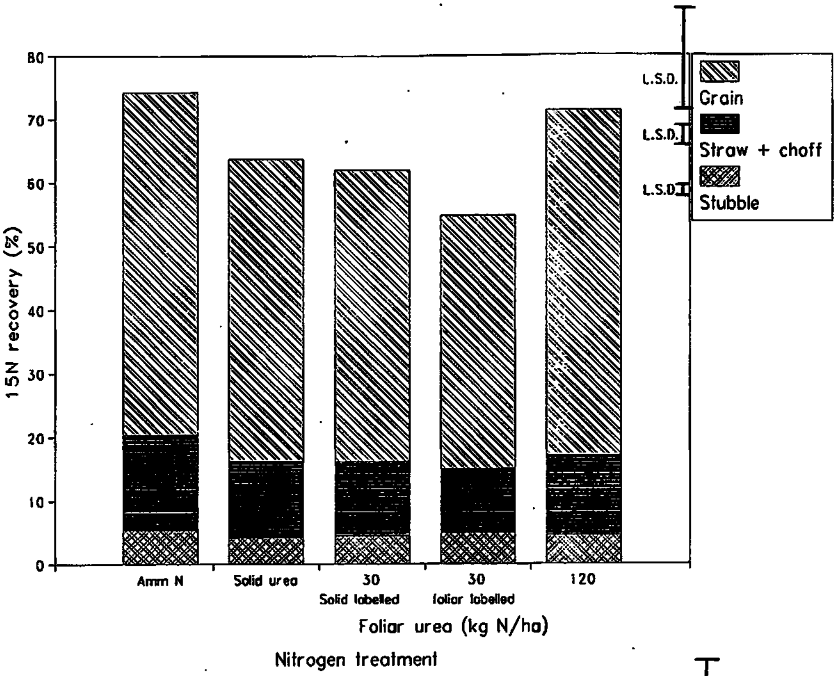


Figure 4.2 Percentage recovery of ^{15}N-labelled fertiliser in the above ground crop in 1993

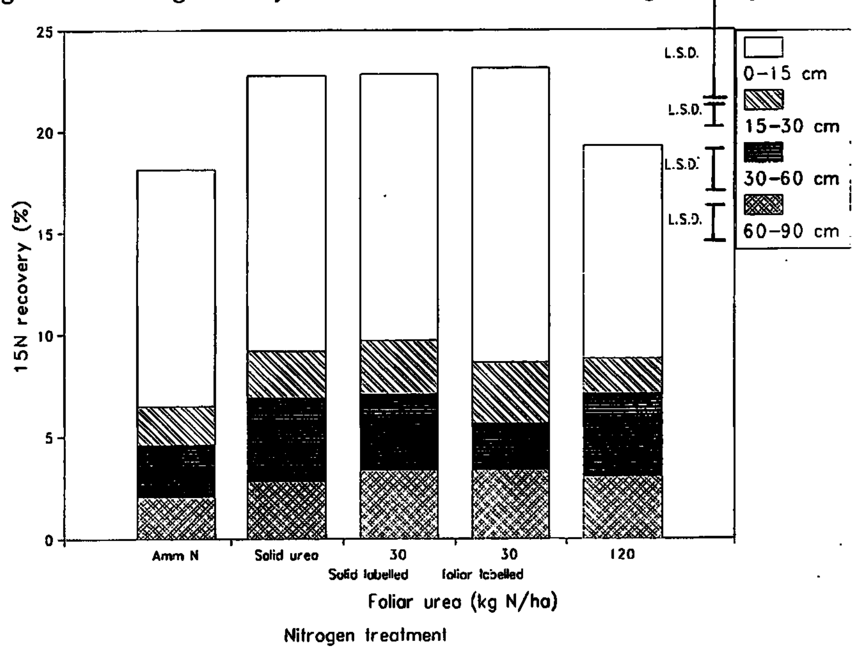


Figure 4.3 Percentage recovery of ^{15}N-labelled fertiliser in the soil in 1993

4.4 Discussion

Grain yields for the treatments in this experiment as calculated from the ^{15}N microplots, were similar to the yields recorded for the corresponding treatments in the main plots. Total above ground dry matter, however, was higher and harvest index was therefore slightly lower.

Recovery of labelled fertiliser N in the above ground crop of between 39-87% (mean 63%) has been reported for a range of rates of solid N applied in the spring to winter wheat (Powlson *et al.*, 1986a; MacDonald *et al.*, 1989 and Powlson *et al.*, 1992). Corresponding recovery in the soil to 70 cm averaged 18%. Recovery of labelled fertiliser N in the crop (average 65%) and soil (average 21%) recorded in this experiment is therefore in the order reported by others.

On average over all the treatments, apparent nitrogen recovery as calculated from the ^{15}N labelled microplots was some 3% higher than that calculated from the main plots for the corresponding treatments in the main experiment. This may be attributed to the inclusion of N in the stubble in the calculation of apparent N recovery for the ^{15}N labelled microplots, but not for the main plots. Allowing for this, apparent N recovery as calculated for the corresponding treatments in the two experiments is in reasonable agreement. Apparent recovery of fertiliser N as reported in the literature is usually higher than the corresponding true recovery. In this experiment, apparent nitrogen recovery for the treatments as calculated from the ^{15}N labelled microplots was 2 to 13% higher than the true recovery of ^{15}N labelled fertiliser.

If it is assumed that the unlabelled N applied to the treatments was recovered with the same efficiency as the labelled N, then it is possible to estimate N in the crop derived from fertiliser. Subtracting fertiliser N in the crop as estimated by this method from the total N in the above ground crop gives a crude estimate of the amount of N taken up by the crop derived from mineralisation of soil organic matter. The calculation shows that on average over all the treatments 88 kg/ha of native soil mineral N was absorbed by the crop. Corresponding uptake of soil mineral N by the zero N treatment in the main experiment was 76 kg/ha. The extra 12 kg N/ha taken up by the fertiliser treated plots could be a real effect, due to increased root growth or increased mineralisation of soil organic N due to the added fertiliser N; or it could be an apparent effect caused by pool substitution. Jenkinson *et al.* (1985) gives a fuller discussion of these effects. The early unlabelled N, however, is unlikely to have been recovered with the same efficiency as the later labelled N and further, the error associated with this calculation is greater the larger the proportion of unlabelled N applied. The estimate of increased uptake of soil mineral N, be it real or apparent, must therefore be treated with considerable caution and it would be difficult to have any confidence in differences in uptake of soil mineral N between treatments as calculated by this method.

Poulton *et al.* (1990) recorded lower overall recovery of fertiliser N in the crop and soil for N applied as foliar urea compared to soil applied urea ammonium nitrate. Recovery of labelled N in the above ground crop was similar, 40-46% in the grain and 8-11% in the straw (+ chaff), but less N was recovered in the soil for the foliar than for the soil applied N, 1-11% and 25% respectively. The results of this experiment support these findings with respect to recovery of labelled fertiliser N in the crop. In this experiment percentage recovery of fertiliser N in the crop was higher than that reported by Poulton *et al.* (1990), largely due to higher above ground dry matter production (N concentration of the dry matter was similar), but percentage recovery in the crop was similar for soil and foliar applied N. However, percentage recovery of labelled fertiliser N in the soil recorded in this experiment was not significantly different for N applied to the soil and to the foliage.

Poulton *et al.* (1990) tentatively implicated (1) the translocation of some of the foliar applied N to the roots - soil samples were only taken to a depth of 5 cm for the foliar treatments, and (2) volatilisation from the foliar treatments, as reasons for the lower overall unaccounted for N. In the experiment described here soil samples were taken to 90 cm for all treatments, and though there is an indication from the data that recovery of labelled N below the plough layer was greater for N applied as urea compared to N applied as ammonium nitrate, the effect is very small and would not account for the 7-17% higher losses for foliar N reported by Poulton *et al.* (1990). Foliar applications were made in this experiment between 26 April and the 10 May corresponding to GS 31-33. In the experiment of Poulton *et al.* (1990), foliar applications were made between 9 May and 18 June corresponding to GS 31-51. In the experiment reported here then, foliar applications were made approximately one month earlier to a less advanced crop. Factors affecting ammonia volatilisation have been reviewed (section 2.2.2 (iii)). Ammonia volatilisation from urea fertiliser depends on surface moisture content due to the requirement of hydrolysis for water (Volk, 1966; Mahli and Nyborg, 1979; Fergusson and Kissel, 1986). Once hydrolysed, volatilisation of ammonia increases with temperature and windspeed (Haynes and Sherlock, 1986). It is likely therefore, that the potential for volatilisation losses following urea hydrolysis in this experiment would have been lower than in the experiment of Poulton *et al.* (1990), due to the earlier application of foliar urea in cooler conditions, and application in the evening rather than the day with lower temperatures and reduced windspeeds overnight following application.

Further, it is likely that difference in time of application of foliar sprays is also implicated in the apparently conflicting results with respect to N losses recorded for year 1 and year 2 in the main experiment. The results for the main experiment in 1992 indicated that the lower apparent recovery of fertiliser N in the crop-soil mineral N system as the rate of N applied as foliar urea increased, was due to immobilisation of fertiliser N in the soil organic matter and / or gaseous losses from the leaf / soil surface. The results from the ^{15}N experiment indicate that total recovery of fertiliser N in the soil is similar for N applied as solid ammonium nitrate or urea to the soil and for N applied as foliar urea. If it is assumed that the mineralisation \ immobilisation balance for <u>fertiliser N</u> in the soil following application was similar in 1992 and 1993 then the implication is, that the lower apparent recovery of N in the plant-soil mineral N system as the rate of N applied as foliar urea increased recorded in 1992, is likely to have been due to higher gaseous losses. That no evidence was found in this experiment to support this can be related to differences in time of application of foliar sprays. As already discussed (section 3.2.4, p 150), the earlier application of the foliar urea sprays this year compared to 1992, and application in the evening, would have been less conducive to gaseous losses.

Recovery of fertiliser N in the soil as recorded in this experiment reflects total fertiliser N in the soil at harvest i.e. fertiliser N in the mineral and organic N fractions. MacDonald *et al.* (1989) have shown that of the fertiliser N applied to winter wheat in the spring, on average, only 1% is present in mineral forms in the soil at harvest. Differences in recovery of fertiliser N as recorded in this experiment cannot therefore necessarily be related to differences in soil mineral N levels and nitrate leaching over the subsequent winter as recorded for the corresponding treatments in the main experiment.

5.0 N-TIMING EXPERIMENT

In the main experiment, as the rate of N applied as foliar urea increased an increasing proportion of the total N was applied later. Results obtained in the main experiment, may therefore be a reflection of either the rate of N applied as foliar urea i.e. soil application vs foliar application, or time of application in relation to crop development. A field experiment was therefore carried out in 1993 to determine for selected treatments in the main experiment the effect of time of application of foliar urea.

5.1 Field Treatments

Winter wheat (*Triticum aestivum* cv. Beaver) was drilled into a sandy loam soil (Bridgnorth series) on Swans Leasow field at Harper Adams on 10 October 1992. The field had previously been in winter wheat. Seedbed cultivations consisted of straw incorporation by ploughing to 20 cm and pressing followed by a Rotera type cultivation. C2 seed treated with Baytan seed dressing was drilled using a Nordsten drill with a coulter spacing of 11.25 cm.

Treatments 1, 2, 3, 5, 6, and 7 as in the main experiment (zero N, solid ammonium nitrate, solid urea, 50%, 75%, and 100% of the main N application as foliar urea) were repeated. For foliar treatments, time of application of foliar urea was either as per the main experiment or all on a single date at GS 31. Treatments are summarised in Table 5.1.

All treatments except zero N received 50 kg N/ha in early March. Solid ammonium nitrate (Nitram 34.5% w/w) and solid urea (Seabright 46% w/w) were applied to the plots by hand. Foliar urea was applied as Nufol (20% w/v) at 30 kg N/ha in 300 l/ha i.e. 150 l Nufol + 150 l water. For treatments receiving foliar N as per the main experiment, the objective was to apply

Table 5.1 Nitrogen treatments in the N-timing experiment 1993

Trt. No.	N in early March (kg N/ha)		N at GS 31 (kg N/ha)			Total N (kg/ha)
	Rate	Form	Rate	Form	Timing	
1	0	-	0	-	-	0
2	50	Solid ammonium nitrate	120	Solid ammonium nitrate	GS 31	170
3	50	Solid urea	120	Solid urea	GS 31	170
4	50	Solid urea	60	Solid urea	GS 31	
			60	Foliar urea	Single date	170
5	50	Solid urea	60	Solid urea	GS 31	
			60	Foliar urea	As per main expt.	170
6	50	Solid urea	30	Solid urea	GS 31	
			90	Foliar urea	Single date	170
7	50	Solid urea	30	Solid urea	GS 31	170
			90	Foliar urea	As per main expt.	
8	50	Solid urea	120	Foliar urea	Single date	170
9	50	Solid urea	120	Foliar urea	As per main expt.	170

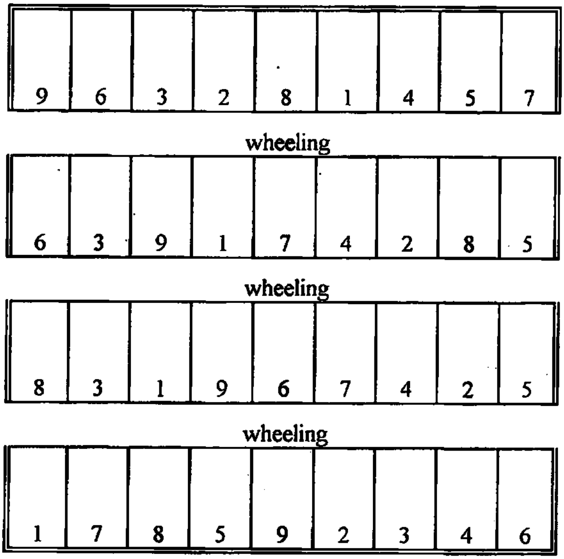
30 kg N/ha every 4 to 5 days starting at GS 31 to give the required rate of foliar N according to treatment. For treatments receiving foliar N on a single date at GS 31, the objective was to apply 30 kg N/ha every 3 to 4 hours to give the required rate of foliar N. However, due to unfavourable spraying conditions (wind) around mid day on the first spray date only 2 sprays were applied, in the morning and evening, and rainfall on the following 3 days prevented further application of foliar urea. The balancing sprays for the 90 and 120 kg N/ha foliar urea treatments were therefore actually applied 3 days after the first two sprays. Actual dates and growth stages of N applications are given in Table 5.2. All foliar urea applications were made through flat fan nozzles using an Oxford precision sprayer, as for the main experiment.

Table 5.2 Dates of N applied in the N-timing experiment 1993

		TREATMENT								
					Single date of application			Application as per main experiment		
Date Applied	ZGS	Zero-N	NH_4NO_3 (kg N/ha)	Solid urea (kg N/ha)	60 kg N/ha Foliar urea	90 kg N/ha Foliar urea	120 kg N/ha Foliar urea	60 kg N/ha Foliar urea	90 kg N/ha Foliar urea	120 kg N/ha Foliar urea
18/3	24		50	50S	50S	50S	50S	50S	50S	50S
21/4	30/31		120	120S	60S	30S	-	60S	30S	-
22/4	30/31				30F, 30F	30F, 30F	30F, 30F	30F	30F	30F
26/4	31					30F	30F, 30F	-	-	-
27/4	31							30F	30F	30F
2/5	31								30F	30F
7/5	32									30F
Total		0	170	170	170	170	170	170	170	170

S = Urea applied as solid F = Urea applied as foliar spray

Treatments were replicated four times in a randomised block design. Plots were 3 x 9 m, adjacent blocks separated by a wheeling (Figure 5.1).



9	6	3	2	8	1	4	5	7

wheeling

6	3	9	1	7	4	2	8	5

wheeling

8	3	1	9	6	7	4	2	5

wheeling

1	7	8	5	9	2	3	4	6

Figure 5.1 Plot layout and randomisation for the N-timing experiment 1993 (numbers refer to treatments, refer to Table 5.1)

5.2 Sampling and Analytical Techniques

Scorch

For foliar treatments, scorch was assessed 4 to 5 days after each date on which spray was applied. The same method of assessment was used as described for the main experiment (section 3.2.2) and mean values per plot were calculated. For those plots receiving foliar N as per the main experiment, due to the emergence of new leaves between spray applications, percent scorch following each spray was summed to give total scorch attributable to N applied as foliar urea. This figure was then used in the statistical analysis, ensuring comparison of total scorch attributable to foliar N irrespective of timing of application i.e. all at GS 31 or as per the main experiment.

Takeall Assessment

As the crop matured, areas of crop characterised by stunted plants with whiteheads were noted. Examination of the stem base showed this to be attributable to a complex of pathogens involving takeall (*Gaeumanomyces graminis*), brown footrot (*Fusarium culmorum*) and eyespot (*Pseudocercosporella herpotrichoides*). For each plot the percentage area affected was assessed visually.

Lodging

The site was severely affected by lodging in the 2 to 3 weeks prior to harvest. For each plot the angle of lodging and percentage area affected was scored according to the method described by Caldicot and Nuttall (1979) and a lodging index calculated.

Above Ground Plant Dry Matter, Nitrogen & Apparent N Recovery

On 23 August 1993, plants were removed at soil level from two adjacent 0.25 m lengths of row at four positions per plot. Above ground dry matter, above ground N and apparent N recovery were determined as described for the main experiment 1993.

Grain Yield & Grain Protein

The plots were combine harvested on 28 August 1993 using a plot combine and yield adjusted to 85% dry matter.

Statistical Methods

Results were analysed using the Genstat 4 statistical programme. The lodging and takeall data were analysed using analysis of variance and Tukeys test (Sokal and Rohlf, 1981), to determine whether these effects were significantly different between treatments. The reduced lodging for the zero N treatment was significant. This effect was accounted for in subsequent analyses where appropriate, by including lodging index as a covariate in the analysis.

For the other variables measured, a basic analysis of variance was carried out on the full data set, to obtain the best estimate of the error mean square. Data for the zero N, ammonium nitrate and solid urea treatments was then excluded and a second analysis of variance, incorporating the error mean square from the basic analysis of variance, then carried out to test for: any significant effect of rate of N applied as foliar urea on average over the two times of application, any significant effect of time of N application averaged over the three rates of N applied as foliar urea, and any significant interaction between rate of N as foliar urea and time of application on the variable measured. The skeleton analysis of variance for the final analysis is shown in Table 5.3. All significant results are quoted at the 5% level.

Table 5.3 Skeleton analysis of variance for the N-timing experiment 1993

Source of Variation	Degrees of Freedom	
	Apparent N recovery	All other analyses
Blocks	3	3
Rate of N applied as foliar urea	2	2
Timing	1	1
Rate of N applied as foliar urea x Timing	2	2
Residual (from basic ANOVA)	21	24

Lodging score was included as a covariate in the basic analysis of variance of the yield and harvest index data, to account for the significantly lower lodging for the zero N treatment.

5.3 Results

Takeall and Lodging (Table 5.4)

The plots were badly infected by takeall disease. On average 30 % of the plot area was infected for N treated plots and infection was higher for the zero N treatment, with 50% of the plot area infected. Differences in level of infection between treatments, however, were not significant.

The site also suffered severe lodging 2-3 weeks prior to harvest. Lodging was highest for the ammonium nitrate treated plots (89% of the plot area lodged) and least for plots receiving no N (<1% of the plot area lodged). For the urea treatments, lodging incidence ranged from 70 - 43% of the plot area. The reduced lodging for the zero N treatment was significant compared to the other treatments. Other differences between treatments were not significant.

Table 5.4 Takeall and lodging incidence for selected N treatments in the main experiment applied as per the main experiment or all at GS 31 in 1993

Treatment	Takeall (% plot area affected)		Lodging (%plot area affected)	
	Timing		Timing	
	as main expt.	all @ GS 31	as main expt.	all @ GS 31
Zero N	51.3		0.7	
Ammonium nitrate	25.0		88.7	
Solid urea	27.5		57.8	
60 kg N/ha foliar urea	22.5	32.5	65.9	70.1
90 kg N/ha foliar urea	37.8	33.8	60.4	50.3
120 kg N/ha foliar urea	33.8	25.3	42.5	62.1
S.E.M.	9.69		8.68	
C.V. (%)	60.3		31.3	

Yield (Table 5.5)

Yield for the zero N treatment was higher than expected and, on average over all N treatments, there was no significant response to N application.

Despite the incidence of takeall and lodging at the site, yields for the N treatments on average, were similar to those for the main site. On average, within the foliar treatments, there was no significant effect on yield of either time of N application or rate of N applied as foliar urea. Further, there was no significant interaction between rate of N applied as foliar urea and time of application.

Table 5.5 Yield (t/ha) for selected N treatments in the main experiment applied as per the main experiment or all at growth stage 31 in 1993

Treatment	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
Zero N	6.77		
Ammonium nitrate	7.97		
Solid urea	8.78		
60 kg N/ha as foliar urea	9.16	8.79	8.98
90 kg N/ha as foliar urea	8.75	8.91	8.83
120 kg N/ha as foliar urea	9.18	8.95	9.06
Mean (timing)	9.03	8.88	
C.V. (%)	10.8		

	Rate	Timing	Rate x Timing
S.E.M.	0.328	0.268	0.464

Above Ground Dry Matter Production (Table 5.6)

As expected given the high yield, total above ground dry matter production for the zero N treatment was also very high, and was not significantly different from the N treatments on average.

Within the foliar treatments on average over the two times of application, there was no significant effect on dry matter production as the rate of N applied as foliar urea increased; and averaged over the three rates of N applied as foliar urea, time of application had no significant effect on dry matter production. There was no significant interaction between rate of N applied as foliar urea and N timing.

Table 5.6 Above ground dry matter production (t/ha) for selected N treatments in the main experiment applied as per the main experiment or all at growth stage 31 in 1993

Treatment	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
Zero N	15.89		
Ammonium nitrate	16.10		
Solid urea	18.45		
60 kg N/ha as foliar urea	19.01	18.90	18.96
90 kg N/ha as foliar urea	18.05	18.94	18.50
120 kg N/ha as foliar urea	20.28	18.72	19.50
Mean (timing)	19.11	18.85	
C.V. (%)	12.1		

	Rate	Timing	Rate x Timing
S.E.M.	0.782	0.638	1.106

Harvest Index (Table 5.7)

Within the foliar treatments, there was no significant effect on harvest index on average, of either time of application or rate of N applied as foliar urea and no significant interaction between rate of N as foliar urea and timing was found.

Table 5.7 Harvest Index for selected N treatments in the main experiment applied as per the main experiment or all at growth stage 31 in 1993

Treatment	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
Zero N	0.411		
Ammonium nitrate	0.519		
Solid urea	0.481		
60 kg N/ha as foliar urea	0.485	0.468	0.477
90 kg N/ha as foliar urea	0.493	0.473	0.483
120 kg N/ha as foliar urea	0.460	0.487	0.473
Mean (timing)	0.479	0.476	
C.V. (%)	11.0		

	Rate	Timing	Rate x Timing
S.E.M.	0.0186	0.0152	0.0263

Scorch

Table 5.8 shows the mean scorch recorded five days after each spray application and total scorch due to the full spray application. Scorch was very low for all treatments, less than 2% in all cases.

Following the first spray, scorch was generally higher for those treatments receiving all of their foliar application of N on that date compared to those treatments where the foliar application was applied as per the main experiment. For those treatments receiving foliar N as per the main experiment, the level of scorch recorded generally increased with later applications, however, the maximum level of scorch recorded for 120 kg N/ha applied as per the main experiment following the final spray, was still less than 2%.

Considering total scorch, on average over the two times of application, scorch significantly increased as the rate of N applied as foliar urea increased, while on average over the three rates of N applied as foliar urea, scorch was significantly higher for N applied as per the main experiment compared to N applied all at GS 31. There was also a significant interaction between rate of N as foliar urea and timing, the increase in scorch with increasing rate of N applied as foliar urea was greater for N applied as per the main experiment compared to N applied all at GS 31.

Table 5.8 Scorch for selected foliar urea treatments in the main experiment applied as split applications and all at GS 31 in 1993

Treatment	Scorch following each spray (%)				
	spray 1	spray 2	spray 3	spray 4	Total
60 kg N/ha applied all @ GS 31	1.15				1.15
90 kg N/ha applied all @ GS 31	0.31				0.31
120 kg N/ha applied all @ GS 31	0.71				0.71
60 kg N/ha applied as per main expt.	0.1	0.27			0.38
90 kg N/ha applied as per main expt.	0.23	0.29	0.42		0.94
120 kg N/ha applied as per main expt.	0.16	0.20	0.52	1.63	2.51
S.E.M.					
Rate of N as foliar urea					0.168
Timing					0.137
Rate of N as foliar urea x Timing					0.237
C.V. (%)					5.5

Above Ground Plant N (kg/ha in the dry matter) (Table 5.9 and 5.10)

Above ground plant N for the zero N treatment was not significantly different from those treatments that received nitrogen. N content of the above ground dry matter was similar for all treatments. The lack of any significant response to nitrogen application with respect to above ground plant N reflects the unusually high dry matter production recorded for the zero N treatment.

Within the foliar treatments, effect on above ground N of time of application and rate of N applied as foliar urea was not significant, neither was there any significant interaction between time of application and rate of N applied as foliar urea.

Table 5.9 Above ground plant N (kg N/ha) for selected N treatments in the main experiment applied as per the main experiment or all at growth stage 31 in 1993

Treatment	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
Zero N	192.4		
Ammonium nitrate	242.2		
Solid urea	264.4		
60 kg N/ha as foliar urea	284.9	284.2	284.5
90 kg N/ha as foliar urea	241.9	276.0	259.0
120 kg N/ha as foliar urea	275.2	272.5	273.8
Mean (timing)	267.3	277.6	
C.V. (%)	16.4		

	Rate	Timing	Rate x Timing
S.E.M.	15.01	12.26	21.23

Table 5.10 N concentration in the dry matter (%) for selected N treatments in the main experiment applied as per the main experiment or all at growth stage 31 in 1993

Treatment	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
Zero N	1.210		
Ammonium nitrate	1.514		
Solid urea	1.436		
60 kg N/ha as foliar urea	1.495	1.507	1.501
90 kg N/ha as foliar urea	1.355	1.450	1.402
120 kg N/ha as foliar urea	1.339	1.455	1.397
Mean (timing)	1.396	1.470	
C.V. (%)	8.3		

	Rate	Timing	Rate x Timing
S.E.M.	0.0414	0.0338	0.0586

<u>Apparent Recovery of Fertiliser N in the Above Ground Crop</u> (Table 5.11)

Apparent recovery of fertiliser N in the above ground crop was lowest for the ammonium nitrate treatment (29%) and highest for the 60 kg N/ha foliar urea treatment (54%). In all cases, apparent recovery of fertiliser N in this experiment was lower than recorded for the same treatment at the main site.

Within the foliar treatments, apparent recovery of fertiliser N was not affected by time of application or rate of N applied as foliar urea.

Table 5.11 Apparent N recovery (%) for selected N treatments in the main experiment applied as per the main experiment or all at growth stage 31 in 1993

Treatment	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
Ammonium nitrate	29.4		
Solid urea	42.4		
60 kg N/ha as foliar urea	54.4	54.0	54.2
90 kg N/ha as foliar urea	29.2	49.2	39.2
120 kg N/ha as foliar urea	48.7	47.1	47.9
Mean (timing)	44.1	50.1	
C.V. (%)	58.8		

	Rate	Timing	Rate x Timing
S.E.M.	9.21	7.52	13.02

5.4 Discussion

Yield, Above Ground Dry Matter and Harvest Index

The data from the main experiment this year and in 1992 suggests that the physiological response of winter wheat to foliar urea is due to compensating effects on above ground dry matter production and harvest index according to time of application: where the rate of N applied as foliar urea is relatively low and therefore a larger proportion of the total N is applied early, above ground dry matter production is increased but harvest index is reduced. Conversely, where the rate of N applied as foliar urea is relatively high, and therefore a proportion of the total N is applied later, above ground dry matter production is reduced but harvest index is higher and yield is maintained.

For N applied all at GS 31, the similar yield, above ground dry matter production and harvest index for the foliar urea treatments was as expected. However, due to the early application of all of the foliar urea, above ground dry matter production would have been expected to increase and harvest index to decrease compared to the corresponding treatments where the foliar urea was applied at the same time as the main experiment. Further, the effect on above ground dry matter production and harvest index would be expected to have been larger the higher the rate of N applied as foliar urea. This was not found: on average, time of application as in the main experiment or all at GS 31, had no significant effect on above ground dry matter production or harvest index and there was no interaction between rate of N applied as foliar urea and time of application.

The results from this experiment therefore provide no evidence to support the hypothesis that the effect of foliar urea on above ground dry matter and harvest index depends upon time of application. However, due to the tighter spray programme this year compared to 1992, such that all foliar applications were made to the crop at GS 31 or 32, the actual difference in timing of application between the foliar sprays applied as per the main experiment and those applied all at GS 31, was very small. It is logical to expect therefore that differences in above ground dry matter and harvest index for N applied as per the main experiment and N applied all at GS 31 would have been small.

Therefore, limited differences in time of application for N applied as per the main experiment and all at GS 31, possibly compounded by disease and lodging effects at the site, may account for the lack of any evidence in this experiment to support the hypothesis that the physiological response of winter wheat to foliar urea is due to compensatory effects on above ground dry matter production and harvest index according to time of application.

N Uptake and Apparent Recovery of Fertiliser N

N uptake for the nitrogen treatments was noticeably higher in this experiment than for the corresponding treatments in the main experiment. This was due to higher N concentration in the dry matter, above ground dry matter production was similar for the two sites. Apparent recovery of fertiliser N, however, was lower, averaging 44% for all N treatments. The lower apparent N recovery at this site given the similar above ground dry matter production and growing conditions to the main site, indicates a large supply of N from the soil. The high yield and above ground dry matter production for the zero N plots supports this and soil samples taken at the site in spring 1993 indicated a soil mineral N figure of 82 kg N/ha, compared to 42 kg N/ha (average of all treatments) at the Little Pipe Strine site. The high soil mineral N levels at the site are likely to be a reflection of manure applications according to farm practice in the past.

The objective of this experiment was to determine for selected foliar urea treatments, whether effects on above ground dry matter and harvest index observed in the main experiment were due to the rate of N applied as foliar urea, or time of application of N in relation to crop development. In addition to the limited difference in time of application for N applied as per the main experiment or all at GS 31 achieved in this experiment, it is likely that reduced uptake of fertiliser N at this site compared to the main experiment site, as indicated by the lower apparent N recovery data, would have further limited any effects on above ground dry matter production and harvest index of time of application of fertiliser N.

6.0 INTERCEPTION EXPERIMENT

Given the limited leaf cover available for spray interception at the time of N application in the main experiment, the proportion of urea applied as a foliar spray that is actually intercepted by the foliage may be small. Further, differences in crop response and N recovery recorded in the main experiment may be due to differences in interception of the foliar applied urea as a result of a larger proportion of N applied later as the rate of N applied as foliar urea increases.

An experiment was therefore carried out to determine for selected treatments in the main experiment, the amount of N intercepted by the foliage and that deposited on the ground. Further, due to the problems of lodging and disease associated with the 1993 N-timing experiment, for two of the treatments N was applied as per the main experiment or all at GS 31, to determine any differences in crop response arising due to time of application and to determine whether this was related to differences in interception.

6.1 Field Treatments

The experiment was located on Little Pipe Strine field, Tibberton Manor Farm , Edgmond adjacent to the N-rate experiment. Crop and establishment details were as given for the main experiment 1994 (section 3.3.1).

Treatments 1,5,6,7 and 8 as in the main experiment (zero N, 50%, 75%, 100% of the main N application as foliar urea and the all foliar urea treatment) were repeated. For 50% and 100 % of the main N application as foliar urea, the objective was to apply N either as per the main experiment or all on a single date at GS 31. Treatments are summarised in Table 6.1.

Table 6.1 Nitrogen treatments in the interception experiment 1994

Trt. No.	N in early March (kg N/ha)		N at GS 31 (kg N/ha)			Total N (kg/ha)
	Rate	Form	Rate	Form	Timing	
1	0	-	0	-	-	0
2	50	Solid urea	60 60	Solid urea Foliar urea	GS 31 As per main expt.	170
3	50	Solid urea	60 60	Solid urea Foliar urea	All at GS 31	170
4	50	Solid urea	30 90	Solid urea Foliar urea	GS 31 As per main expt.	170
5	50	Solid urea	120	Foliar urea	As per main expt.	170
6	50	Solid urea	120	Foliar urea	All at GS 31	170
7	50	Foliar urea	120	Foliar urea	As per main expt.	170

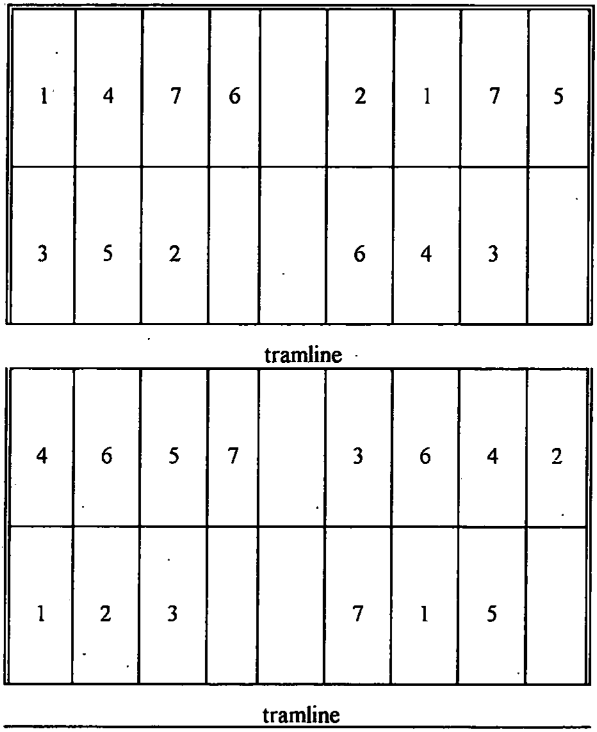
All treatments except zero N received 50 kg N/ha in early March. Solid ammonium nitrate (Nitram 34.5% w/w) and solid urea (Seabright 46% w/w) were applied to the plots by hand. Foliar urea was applied as Nufol (20% w/v) at 30 kg N/ha in 300 l/ha i.e. 150 l Nufol + 150 l water. Foliar urea applications were made through flat fan nozzles using an Oxford precision sprayer, as for the main experiment. For treatments receiving foliar N as per the main experiment, the objective was to apply 30 kg N/ha every 4 to 5 days starting at GS 31 to give the required rate of foliar N according to treatment. For treatments receiving foliar N on a single date at GS 31, the objective was to apply 30 kg N/ha every 3 to 4 hours to give the required rate of foliar N, however, increased wind speeds in the middle of the day meant that foliar urea applications to treatment 6 were spread over two days rather than 1 day as intended. Actual dates and growth stages of N applications are given in Table 6.2.

Table 6.2 Dates of N applied in the interception experiment 1994

		TREATMENT						
ZGS	Date Applied	Zero-N	60 kg N/ha Foliar urea As per main expt.	60 kg N/ha Foliar urea All at GS 31	90 kg N/ha Foliar urea As per main expt.	120 kg N/ha Foliar urea As per main expt.	120 kg N/ha Foliar urea All at GS 31	170 kg N/ha Foliar urea As per main expt.
22	10/3							30F
22	12/3		50S	50S	50S	50S	50S	
22/23	16/3							20F
30/31	21/4		30F	30F 30F	30F	30F	30F 30F	30F
30/31	22/4						30F 30F	
30/31	24/4		60S	60S	30S			
31	26/4		30F		30F	30F		30F
31	1/5				30F	30F		30F
32	6/5					30F		30F
Total		0	170	170	170	170	170	170

S = Urea applied as solid   F = Urea applied as foliar spray

Plots were 3 x 9 m and treatments were replicated four times in a randomised block design as shown in Figure 6.1.



1	4	7	6		2	1	7	5
3	5	2			6	4	3	

tramline

4	6	5	7		3	6	4	2
1	2	3			7	1	5	

tramline

Figure 6.1 Plot layout and randomisation in the interception experiment 1994 (numbers refer to treatments, refer to Table 6.1)

6.2 Sampling and Analytical Techniques

Interception of Urea Spray by Foliage and Soil

The volume of spray intercepted by the foliage and that falling on the soil surface was determined by adding sodium fluorescein to the foliar urea spray to act as a tracer. For the early N applied as foliar urea to the all foliar urea treatment, a concentration of 1 g of sodium fluorescein per 10 l of urea spray solution was used, however, on the basis of the results obtained, this was reduced to 0.01 g / 10 l in subsequent spray applications. Spray interception by the foliage and soil was determined using a method adapted from that described by Hislop *et al.* (1993). Full details of the method used in this experiment are given below.

Interception by the foliage was determined by measuring fluorescein deposition on plant samples collected immediately after spraying. Plants from two adjacent 0.25 m lengths of row were cut at soil level at four positions per plot immediately after spraying. The samples were placed in plastic bags and stored in the dark prior to extraction. Fluorescein was washed off the plant surface by soaking the plant material in 250 ml of an extract solution containing 2 ml/l 1N NaOH + 1 ml/l Agral (Zeneca Crop Protection Ltd.) for 10 minutes. A 25 ml sub sample of the wash-off solution was collected and stored frozen in the dark prior to fluorometric analysis. To take account of any background fluorescence arising from residual fluorescein due to previous sprays and / or natural fluorescence of the plant material itself, control samples of plant material were collected from the plots immediately prior to spraying. Four control samples were taken per plot by harvesting plant material from two adjacent 0.25 m lengths of row as above. Storage and fluorescein extraction was as described above.

Spray deposition on the ground was determined by measuring fluorescein deposition on strips of chromatography paper (Whatman Cr 1, 56.7 cm x 5 cm) attached to wooden battens placed on the ground at four random positions per plot. Battens were placed along the rows, taking care not to disturb the foliage, at right angles to the direction of spray travel. Immediately after spraying, the paper strips were placed in plastic bags and stored in the dark prior to fluorescein extraction. Fluorescein extraction was as for the plant material, but a 50 ml volume of extract solution was used. A 25 ml sub sample of the wash-off solution was collected and stored frozen in the dark prior to analysis. To take account of any background fluorescence of the chromatography paper, on each sample date four unsprayed paper strips were extracted to act as controls. A sample of the labelled foliar urea spray solution was collected from the tank on each spray date. The volume of spray intercepted by the plant or paper sample was determined using a Spectrofluorimeter (Perkin Elmer Luminescence Spectrometer LS 30) calibrated using a dilution series of the appropriate tank sample.

Above Ground Dry Matter at Harvest

On 12 August 1994, plants from two adjacent 0.5 m lengths of row were cut at soil level from four positions in each plot. The samples were bulked and dried at 80 ^{0}C for 48 hours. Total above ground dry matter was calculated using row width to determine sampling area.

Above Ground Plant N

20 whole plant stems were randomly selected from the dried bulk sample and above ground plant N determined. Details of the analysis were as given for the main experiment 1992 (section 3.1.2). Apparent recovery of fertiliser N in the above ground plant dry matter was calculated for each plot.

Grain Yield

The plots were combine harvested on 15 August 1994 using a plot combine and yield adjusted to 85% dry matter.

Statistical Methods

Results were analysed using the Genstat 4 statistical programme. A basic analysis of variance was carried out on the full data set, to obtain the best estimate of the error mean square. Two further analyses of variance were then carried out, on the appropriate restricted data set, but incorporating the error mean square from the basic analysis of variance, to test for:

i) Any significant linear, quadratic, cubic relationship between the rate of N applied as foliar urea and the variable measured. The skeleton analysis of variance for this analysis is shown in Table 6.3

ii) Any significant effect of rate of N applied as foliar urea on average over the two times of application, any significant effect of time of application averaged over the two rates of N applied as foliar urea and any significant interaction between rate of N applied as foliar urea and timing for the variables measured. The skeleton analysis of variance for this analysis is shown in Table 6.4.

Table 6.3 Skeleton analysis of variance for the interception experiment: polynomial contrasts for N applied as per the main experiment

Source of Variation	Degrees of Freedom		
	Interception	Apparent N recovery	All other analyses
Blocks	3	3	3
Linear	1	1	1
Quadratic	1	1	1
Cubic	1	1	1
Residual (from basic ANOVA)	15	15	18

Table 6.4 Skeleton analysis of variance for the interception experiment: main effects and interactions of rate of N applied as foliar urea and timing

Source of Variation	Degrees of Freedom		
	Interception	Apparent N recovery	All other analyses
Blocks	3	3	3
Rate of N applied as foliar urea	1	1	1
Timing	1	1	1
Rate of N applied as foliar urea x Timing	1	1	1
Residual (from basic ANOVA)	15	15	18

6.3 Results

Yield, Above Ground Dry Matter and Harvest Index (Tables 6.5 - 6.8)

Yields for the treatments in this experiment were approximately 1 t/ha higher than the corresponding treatments in the main experiment at the same site. For urea applied as per the main experiment, there was no significant difference in yield as the rate of N applied as foliar urea increased. Above ground dry matter and harvest index, however, showed significant and contrasting trends as the rate of N applied as foliar urea increased. Above ground dry matter decreased in a cubic manner, decreasing for 90 kg N/ha as foliar urea, then increasing for 120 kg N/ha as foliar urea before decreasing again for 170 kg N/ha as foliar urea. This trend was significant. Harvest index showed a significant linear increase as the rate of N applied as foliar urea increased.

For the 60 kg N/ha and 120 kg N/ha foliar urea treatments that received N either as per the main experiment or all at GS 31, time of application and rate of N applied as foliar urea had no significant effect on yield, above ground dry matter or harvest index. Further, there was no significant interaction between rate of N as foliar urea and timing.

Table 6.5 Yield, above ground dry matter production and harvest index for N applied as per the main experiment in the interception experiment 1994

Treatment	Yield (t/ha)	Above ground dry matter (t/ha)	Harvest index
Zero N	2.019	4.73	0.4260
60 kg N/ha as foliar urea	7.54	12.96	0.583
90 kg N/ha as foliar urea	7.55	11.67	0.652
120 kg N/ha as foliar urea	7.57	12.50	0.609
170 kg N/ha as foliar urea	7.20	10.17	0.708
S.E.M.	0.252	0.482	0.246
C.V. (%)	7.1	9.7	8.9

Table 6.6 Yield (t/ha) for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	7.54	7.34	7.44
120 kg N/ha as foliar urea	7.57	7.62	7.59
Mean (timing)	7.55	7.48	
C.V. (%)	7.2		

	Rate	Timing	Rate x Timing
S.E.M.	0.178	0.178	0.252

Table 6.7 Above ground dry matter production (t/ha) for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	12.96	13.43	13.19
120 kg N/ha as foliar urea	12.5	12.53	12.51
Mean (timing)	12.73	12.98	
C.V. (%)	10.1		

	Rate	Timing	Rate x Timing
S.E.M.	0.341	0.341	0.482

Table 6.8 Harvest index for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	0.583	0.550	0.567
120 kg N/ha as foliar urea	0.609	0.609	0.609
Mean (timing)	0.596	0.579	
C.V. (%)	8.5		

	Rate	Timing	Rate x Timing
S.E.M.	0.0174	0.0174	0.0246

Above Ground Plant N (N % & kg N/ha in the dry matter) and Apparent Recovery of N in the Above Ground Dry Matter (Tables 6.9 - 6.12)

For urea applied as per the main experiment, as the rate of N applied as foliar urea increased, differences in N concentration in the dry matter were small. However, a quadratic increase in N concentration as the rate of N applied as foliar urea increased was significant. Total above ground N and apparent N recovery showed a small increase as the rate of N applied as foliar urea increased up to 120 kg N/ha, but then decreased sharply for 170 kg N/ha as foliar urea. This quadratic trend was significant and largely reflects the trend in above ground dry matter production, differences in N concentration being small. Apparent recovery of fertiliser N recorded in this experiment was similar to that recorded for the corresponding treatments in the main experiment.

For the 60 kg N/ha and 120 kg N/ha foliar urea treatments that received N as per the main experiment or all at GS 31, there was no significant effect of time of application or rate of N applied as foliar urea on N concentration, above ground N or apparent N recovery. There was, however, a significant interaction between rate of N applied as foliar urea and timing: For 60 kg N/ha applied as foliar urea, application all at GS 31 increased N concentration, above ground N and apparent N recovery compared to N timing as per the main experiment while for 120 kg N/ha applied as foliar urea, application all at GS 31 decreased N concentration, above ground N and apparent N recovery compared to N timing as per the main experiment.

Table 6.9 N concentration, above ground plant N and apparent N recovery for N applied as per the main experiment in the interception experiment 1994

Treatment	N concentration (%)	Above ground N (kg/ha)	Apparent N recovery
Zero N	0.809	38.5	-
60 kg N/ha as foliar urea	1.077	139.5	59.4
90 kg N/ha as foliar urea	1.202	140.4	59.9
120 kg N/ha as foliar urea	1.197	149.8	65.4
170 kg N/ha as foliar urea	1.131	115.0	45.0
S.E.M.	0.0345	6.96	4.39
C.V. (%)	5.8	11.9	16.6

Table 6.10 N concentration (%) for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	1.077	1.217	1.147
120 kg N/ha as foliar urea	1.197	1.123	1.160
Mean (timing)	1.137	1.170	
C.V. (%)	6.9		

	Rate	Timing	Rate x Timing
S.E.M.	0.0244	0.0244	0.0345

Table 6.11 Above ground plant N (kg N/ha) for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	139.5	163.2	151.4
120 kg N/ha as foliar urea	149.8	140.6	145.2
Mean (timing)	144.7	151.9	
C.V. (%)	12.3		

	Rate	Timing	Rate x Timing
S.E.M.	4.92	4.92	6.96

Table 6.12 Apparent N recovery (%) for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	59.4	73.4	66.4
120 kg N/ha as foliar urea	65.4	60.0	62.7
Mean (timing)	62.4	66.7	
C.V. (%)	16.6		

	Rate	Timing	Rate x Timing
S.E.M.	3.10	3.10	4.39

N Interception by the Foliage and Soil (Tables 6.13 - 6.17)

Examination of the interception data by spray date, as shown in Table 6.13, shows that as expected, interception of N by the foliage increased and interception by the soil decreased for later spray applications. Despite "foliar" application of N, the data shows that the maximum interception by the foliage on any spray date (mean of all treatments) was only some 35% of the N applied.

For N timing as per the main experiment, there was no significant trend in total interception of N by the foliage plus soil as the rate of N applied as foliar urea increased. The proportion of N intercepted by the foliage decreased as the rate of N applied as foliar urea increased from 60 to 90 kg N/ha, then increased for 120 kg N/ha before showing a large decrease for 170 kg N/ha as foliar urea. This cubic trend was close to significance. The proportion of N reaching the soil decreased slightly up to 120 kg N/ha applied as foliar urea, then showed a large increase for 170 kg N/ha as foliar urea, this trend was significant.

There was no significant effect of time of application or rate of N applied as foliar urea on total N interception by the foliage plus soil. For the 60 kg N/ha and 120 kg N/ha foliar urea treatments that received N as per the main experiment or all at GS 31, there was no significant effect of time of application or rate of N applied as foliar urea on the proportion of N intercepted by the foliage. However, the proportion of N reaching the soil surface, on average over the two rates of N applied as foliar urea, was significantly higher for N applied all at GS 31 compared to N timing as per the main experiment. There was no significant interaction between rate of N applied as foliar urea and timing with respect to the proportion of N intercepted by the foliage, the soil or the foliage plus soil.

Table 6.13 N interception by foliage, soil and foliage plus soil for each spray date (mean of all treatments) in 1994

ZGS	Spray date	N interception by foliage (%)	N interception by soil (%)	N interception by foliage + soil (%)
22	10/3	6.04	79.72	85.76
22/23	16/3	8.73	84.71	93.44
30/31	21-22/4	27.20	78.92	106.12
31	26/4	34.99	48.44	83.43
31	1/5	27.32	49.06	76.38
32	6/5	28.94	57.12	86.08

Table 6.14 N interception by foliage, soil and foliage plus soil for N applied as per the main experiment in 1994

Treatment	N interception by foliage (%)	N interception by soil (%)	N interception by foliage + soil (%)
Zero N	-	-	-
60 kg N/ha as foliar urea	31.1	60.9	92.0
90 kg N/ha as foliar urea	20.2	55.0	75.2
120 kg N/ha as foliar urea	33.2	53.6	86.8
170 kg N/ha as foliar urea	13.9	79.0	92.9
S.E.M.	5.82	3.71	6.50
C.V. (%)	45.6	11.7	15.5

Table 6.15 N interception by foliage (%) for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	31.1	23.1	27.1
120 kg N/ha as foliar urea	33.2	26.1	29.6
Mean (timing)	32.1	24.6	
C.V. (%)	45.0		

	Rate	Timing	Rate x Timing
S.E.M.	4.11	4.11	5.82

Table 6.16 N interception by soil (%) for selected rates of N as foliar urea applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	60.9	76.0	68.5
120 kg N/ha as foliar urea	53.6	78.5	66.0
Mean (timing)	57.2	77.2	
C.V. (%)	13.0		

	Rate	Timing	Rate x Timing
S.E.M.	2.63	2.63	3.71

Table 6.17 N interception by foliage plus soil (%) for selected forms of N applied as per the main experiment or all at GS 31 in 1994

Rate of N as foliar urea	Time of application		
	as main expt.	all @ GS 31	Mean (rate)
60 kg N/ha as foliar urea	92.0	99.2	95.6
120 kg N/ha as foliar urea	86.8	104.6	95.7
Mean (timing)	89.4	101.9	
C.V. (%)	15.1		

	Rate	Timing	Rate x Timing
S.E.M.	4.59	4.59	6.50

6.4 Discussion

Yield, Above Ground Dry Matter and Harvest Index

The higher average grain yield recorded in this experiment compared to the corresponding treatments in the main experiment at the same site, was also noted for the N-rate experiment at the site. The effect was attributed to higher soil mineral N in the spring, due to the site having received a higher rate of N in the previous growing season and the possible influence of change of soil type further along the field and reduced soil compaction. The site used for the interception experiment would similarly have received 215 kg N/ha in the previous growing season, due to standard farm practice, and soil mineral N in the spring could therefore expected to have been higher than at the main site, that received 170 kg N/ha. Further, of the three experiments carried out at the site in 1994, due to increasing clay content from west to east along the field, the interception experiment was located on the heaviest soil. The effect of soil type on yield would have been enhanced this year due to the hot dry growing season. The lack of any significant difference in yield as the rate of N applied as foliar urea increased, agrees with the results of the main experiment and other experiments this year and in previous years.

Time of application of foliar urea in relation to crop development was similar in this experiment to the main experiment. In the context of the hypothesis that foliar urea influences yield by compensatory effects on above ground dry matter production and harvest index according to time of application, trends in above ground dry matter and harvest index as the rate of N applied as foliar urea increased in this experiment would be expected to be similar to those recorded in the main experiment. In fact, trends in above ground dry matter and harvest index in this experiment were in contrast to those recorded in the main experiment. The significant decrease in above ground dry matter and increase in harvest index as the rate of N applied as foliar urea increased, are similar to the trends recorded for the main experiment in 1992, when time of application of foliar urea was delayed. There is no obvious explanation for these apparently contradictory results.

Given the proposed compensatory effects of foliar urea on above ground dry matter production and harvest index according to time of application, the lack of any significant effect on yield on average, for N applied all at GS 31 compared to N applied as per the main experiment, was expected. However, due to the earlier application of foliar urea where the main N application was applied all at GS 31, above ground dry matter production would have been expected to increase and harvest index to decrease compared to the corresponding treatments where the foliar urea was applied at the same time as the main experiment. Further, the effect on above ground dry matter production and harvest index would be expected to have been larger as the rate of N applied as foliar urea increased. This was not found: time of application of foliar urea on average, had no significant effect on above ground dry matter production or harvest index and there was no significant interaction between form and timing. As in the N-timing experiment in 1993 the lack of evidence to support the hypothesis, that the physiological response of winter wheat to foliar urea is due to compensatory effects on above ground dry matter production and harvest index according to time of application, can be related to the limited differences in time of application in relation to crop development for N applied all at GS 31 compared with N applied as per the main experiment. Consideration of the dates of N applied in relation to crop development in Table 6.2, shows that for N applied as per the main experiment a large proportion of the foliar urea was applied at GS 31, and that the largest difference in time of application in terms of crop development was one node, and this for only 25% of the foliar urea applied.

Above Ground Plant N and Apparent N Recovery in the Above Ground Dry Matter

The trend in above ground N and apparent N recovery as the rate of N applied as foliar urea increased largely reflects the trend in above ground dry matter production, differences in N concentration in the dry matter being small. The significant decrease in apparent N recovery for the 170 kg N/ha foliar urea treatment is similar to that recorded for this treatment in the main experiment. In the main experiment this was attributed to N losses associated with application of the early 50 kg N/ha in the morning, which would have been conducive to losses by volatilisation and / or denitrification. In this experiment the early 50 kg N/ha applied as foliar urea was also applied in the morning. The lower apparent N recovery recorded for the 170 kg N/ha treatment in this experiment therefore supports the theory that increased N losses associated with application in the morning compared with the evening are due to increased volatilisation and / or denitrification during the day.

The significant interaction between form and timing with respect to N concentration, above ground N and apparent N recovery arises due to the opposite effect of timing of application on these variables according to the rate of N applied as foliar urea. Due to the increased risk of N losses to the environment, it is logical to speculate that N uptake by the plant would be lower for a single large application of N i.e. all at GS 31, rather than N applied in several small applications i.e. as per the main experiment. The lower N concentration, above ground N and apparent N recovery for N applied all at GS 31, compared to N applied as per the main experiment, recorded for the 120 kg N/ha foliar urea treatment is therefore logical, however, the opposite effect recorded for the 60 kg N/ha foliar urea treatment appears anomalous.

N Interception by the Foliage and Soil

As the rate of N applied as foliar urea increases, the risk of N being lost from the target site due to spray drift increases. While care was taken in all experiments to ensure that spray applications were made under appropriate conditions to minimise drift, the loss of N from the target site with increasing rate of N applied as foliar urea, as a possible confounding factor in these experiments, could not be ruled out. In this experiment, for N timing as per the main experiment, no significant difference in N interception by the foliage plus soil with increasing rate of N applied as foliar urea, indicates that differences in spray drift as the rate of N applied as foliar urea increased were not significant. Variation in total interception (foliage + soil) between treatments, however, was large (Table 6.14) and in cases, considerably less than 100% of the spray was accounted for. The lack of significance, despite relatively large differences between treatments can be related to the high variability of the interception data (c.v. = 45.6%, 11.7% and 15.5%; interception by foliage, soil, and foliage + soil respectively). Limited sample size due to logistical considerations particularly for crop samples, spray drift and the general inaccuracies inherent in hand held spray application techniques in the field, are likely to have been contributory in this respect. These factors are also likely to have been implicated in the considerable variation from 100% of the spray accounted for.

Despite application of N as a "foliar spray", interception by the foliage was relatively low. For N applied around GS 31, only some 30% of the foliar applied N was recovered on the foliage and where all of the N was applied as foliar urea, including the early 50 kg N/ha, foliar interception was reduced to 14%. The lack of significant difference in these results as noted above can be related to the very high variability of the data (c.v. 46%). Interception of "foliar applied" N by the soil reflects the foliage interception data: interception of N by the soil was some 60% for foliar N applications around GS 31 and where the early 50 kg N/ha was applied as foliar urea, interception by the soil increased to nearly 80%.

No studies were found in the literature which have reported interception by the crop or soil of foliar applied urea. Interception by the crop and soil of crop protection chemicals in general has been widely reported. These studies, however, have largely been concerned with relative retention between different methods of application rather than absolute retention by the crop and, due to the typical time of application of these chemicals, few have reported interception data around the time of the main N application i.e. at GS 31. Those studies reporting absolute retention values by the crop at GS 31 have largely used barley as the target crop: Cooke *et al.* (1986 and 1990) and Cooke and Hislop (1987) have reported interception by the foliage of between 43 and 73% for sprays applied to winter barley around GS 31. Given the large morphological differences between barley and wheat at this stage, barley has more tillers and larger leaves, foliar interception for barley would be expected to be higher than for wheat. In addition, these studies used formulated agrochemicals which would be expected to have contained adjuvants to reduce run-off from the leaf surface. Foliar urea in this study, with no adjuvant, would be expected to behave differently, with possibly less spray retained on the leaf. The possible influence of leaf run-off on foliar interception recorded in this study cannot be excluded. From a range of unpublished data, Hislop (1996) considers that <u>maximum</u> foliar interception by wheat at GS 31 is likely to be no more than 40%. Interception by the foliage of 27 - 35%, for foliar urea sprays applied at GS 30 - 32 in this experiment, is therefore in the order expected.

The lower foliar interception and higher soil interception for the all foliar urea treatment can largely be related to the application of the early 50 kg N/ha as foliar urea, when crop cover was limited. Examination of the interception data by spray date (Table 6.13), shows that only 6 - 9% of the early "foliar" N applied at GS 22-23 was intercepted by the foliage. Taylor and Anderson (1987) have reported 90 - 100% recovery of spray on the soil, indicating very low spray interception by the foliage, for a range of spray rates and droplet sizes for a spray solution of Uvitex with water applied to winter wheat at GS 22. In the main experiment in 1992 and 1994 gaseous losses of N following application of the early 50 kg N/ha as foliar urea in the morning, were implicated in the reduced apparent N recovery recorded. For urea intercepted by the foliage, N would have principally been lost by volatilisation (Powlson *et al*, 1987a; Poulton *et al*, 1990), however, for urea falling on the soil , N losses by both volatilisation and denitrification would have been important. From the interception data recorded here, losses of N from the soil surface by denitrification for the early 50 kg N/ha applied as foliar urea may therefore be an important component of any gaseous losses.

In the main experiment, effects on above ground dry matter production and harvest index with increasing rate of N applied as foliar urea, have been related to time of application of N in relation to crop development, a larger proportion of the total N potentially being applied later as the rate of N applied as foliar urea increases. It is reasonable to expect, that the proportion of "foliar applied" N intercepted by the soil and foliage would also vary as the rate of N applied as foliar urea increases. Treatment differences in the main experiment may therefore reflect differences in time of application of N in relation to crop development and / or differences in N deposition on foliage and soil. With the exception of the all foliar urea treatment, where a significant proportion of the foliar N is applied at GS 21, as the rate of N applied as foliar urea increases and a larger proportion of N is therefore applied later, interception by the foliage would be expected to increase and interception by the soil to decrease, due to increasing crop green area index. In this experiment, as the rate of N applied as foliar urea increased from 60 to 120 kg N/ha, there was no clear indication of this from the foliage interception data, however, interception by the soil did show a small but significant decrease. The limited differences in interception of foliar applied N by the foliage and soil are expected, given the limited difference in time of application of foliar urea sprays this year. However, the data indicates that when differences in time of application of foliar sprays are larger as in 1992, differences in the proportion of N intercepted by the foliage and the soil as the rate of N applied as foliar urea increases may be important.

Lower interception by the foliage and higher interception by the soil for N applied all at GS 31 compared to N applied as per the main experiment, on average over the two rates of foliar urea, can be related to earlier application of N for N applied all at GS 31, when crop green area index would be expected to have been lower. That the effect of timing of application was not significant with respect to interception by the foliage, is probably related to the high variability of the foliage interception data, as noted earlier. The effect of time of application on interception by the foliage and soil would be expected to have been greater as the rate of N applied as foliar urea increased i.e. a significant interaction between rate of N applied as foliar urea and timing would have been expected. That no significant interaction between rate of N applied as foliar urea and time of application was found in this experiment for N interception by the foliage or soil, probably reflects the limited differences in time of application in relation to crop development for N applied all at GS 31 compared to N applied as per the main experiment.

Due to the compensatory effect of time of application on interception by the foliage and the soil, the lack of any significant effect of time of application, on average over the two rates of N applied as foliar urea, and no significant interaction between time of application and rate of N applied as foliar urea, with respect to total interception, i.e. interception by the soil plus foliage, was as expected.

7.0 N-RATE EXPERIMENTS

7.1 N-RATE EXPERIMENT 1993

In the main experiment a single rate of N (170 kg N/ha) was applied. Crop response and apparent N recovery for N applied as ammonium nitrate or as different proportions of foliar urea may vary according to the rate of N applied. A field experiment was therefore carried out in 1993, alongside the main experiment, to investigate the effect of N rate on grain yield for selected treatments in the main experiment, and to determine the optimum rate of N (N-opt) for the site.

7.1.1 Field Treatments

The experiment was located approximately 10 m to the east of the main experiment on Little Pipe Strine field, Tibberton Manor Farm, Edgmond. Crop and establishment details were as for the main experiment 1993 (section 3.2.1).

Treatments 1, 2, 3, 4, and 6 as in the main experiment (zero N, solid ammonium nitrate, solid Urea, 25% foliar urea and 75% foliar urea) were repeated. For each nitrogen treatment, N was applied over the range 0 to 240 kg N/ha in equal increments of 60 kg N/ha, to establish the optimum N rate for each treatment. Nitrogen treatments are summarised in Table 7.1.

The experiment consisted of 51 plots arranged in three randomised blocks. Plots were 4 x 10 m, adjacent blocks separated by a 4 m wheeling (Figure 7.1).

Table 7.1 Nitrogen treatments in the N-rate experiment 1993

Trt. No.	N in early March (kg N/ha)		N at GS 31 (kg N/ha)		Total N (kg/ha)
	Rate	Form	Rate	Form	
1	0	-	0	-	0
2	30	Solid ammonium nitrate	30	Solid ammonium nitrate	60
3	30	Solid ammonium nitrate	90	Solid ammonium nitrate	120
4	30	Solid ammonium nitrate	150	Solid ammonium nitrate	180
5	30	Solid ammonium nitrate	210	Solid ammonium nitrate	210
6	30	Solid urea	30	Solid urea	60
7	30	Solid urea	90	Solid urea	120
8	30	Solid urea	150	Solid urea	180
9	30	Solid urea	210	Solid urea	210
10	30	Solid urea	22.5	Solid urea	
			7.5	Foliar urea	60
11	30	Solid urea	67.5	Solid urea	
			22.5	Foliar urea	120
12	30	Solid urea	112.5	Solid urea	
			37.5	Foliar urea	180
13	30	Solid urea	157.5	Solid urea	
			52.5	Foliar urea	240
14	30	Solid urea	7.5	Solid urea	
			22.5	Foliar urea	60
15	30	Solid urea	22.5	Solid urea	
			67.5	Foliar urea	120
16	30	Solid urea	37.5	Solid urea	
			112.5	Foliar urea	180
17	30	Solid urea	52.5	Solid urea	
			157.5	Foliar urea	240

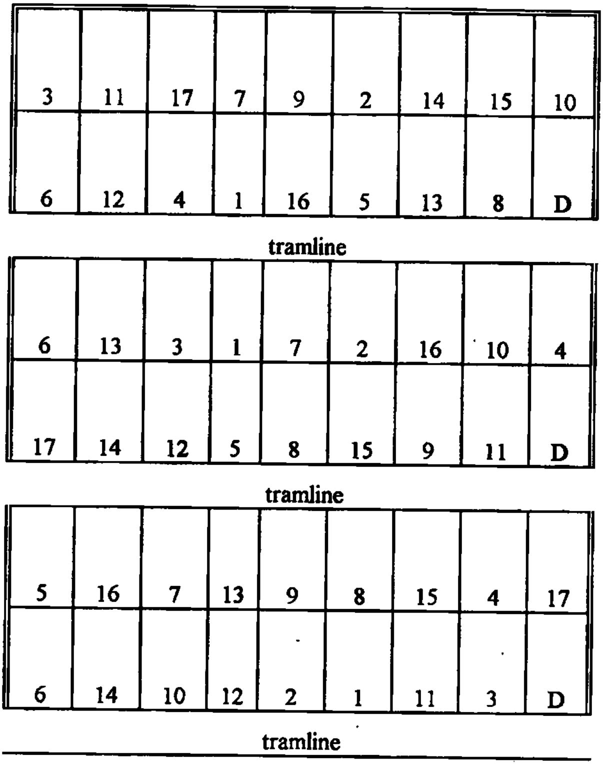


Figure 7.1 Plot layout and randomisation for the N-rate experiment 1993 (numbers refer to treatments, refer to Table 7.1)

All treatments except the zero N treatment received 30 kg N/ha in early March. Solid ammonium nitrate (Nitram 34.5% w/w) and solid urea (Seabright 46% w/w) were applied to the plots by hand. To allow solid applications less than 30 kg N/ha to be spread evenly, the active product was bulked out by adding sharp sand as a filler to give a total weight of material spread equivalent to 30 kg N/ha active product.

The suitability of sharp sand as a filler was confirmed by conducting a simple experiment to compare the coefficient of variation of the weight/m^2 of active product when spread at a rate equivalent to 30 kg N/ha, with the coefficient of variation of active product when spread at the minimum rate but bulked out with sharp sand to a rate equivalent to 30 kg N/ha. Urea was spread at a rate equivalent to 30 kg N/ha on a 6 x 4 m black plastic sheet, and the urea from three randomly selected 1 m^2 areas on the sheet then collected. The samples were weighed and the coefficient of variation of the weight of urea/m^2 calculated. This procedure was repeated with urea spread at a rate equivalent to 7.5 kg N/ha, but bulked out with sharp sand to a rate equivalent to 30 kg N/ha. After collection, each sample (urea + sharp sand) was weighed and the sharp sand then separated by dissolving the sample in water and filtering through a weighed filter paper (Whatman No. 40). The filter papers were then dried overnight at 80^{0}C and reweighed, and the weight of sharp sand determined. The weight of urea in each sample was then determined by difference and the coefficient of variation of the weight of urea/m^2 calculated. The coefficient of variation of the weight of active product/m^2, for urea spread at a rate equivalent to 7.5 kg N/ha plus sharp sand (c.v. = 18.8%) compared favourably with that for urea spread at a rate equivalent to 30 kg N/ha (c.v. = 16%).

Foliar urea was applied as Nufol (20% w/v; NUFOL, Hydro Chafer Ltd., York) diluted with water to give a constant application volume of 300 l/ha. The objective was to apply 30 kg N/ha every 4 to 5 days starting at GS 31 and a final "balance application" to give the required rate of N as foliar urea according to treatment. Actual dates and growth stages of application are given in Table 7.2. Foliar applications were not made to wet leaves or when rain was imminent. All foliar urea applications were made through flat fan nozzles using an Oxford precision sprayer, as for the main experiment.

Table 7.2 Dates of N applied in the N-rate experiment 1993

			TREATMENT															
Date	ZGS	Zero-N	NH_4NO_3				Solid urea				25% Foliar urea				75% Foliar urea			
Applied			(kg N/ha)				(kg N/ha)				(kg N/ha)				(kg N/ha)			
			60	120	180	240	60	120	180	240	60	120	180	240	60	120	180	240
16/3	23		30	30	30	30	30S	30S	30S	30S	30S	30S	30S	30S	30S	30S	30S	30S
19/4	30/31		30	90	150	210	30S	90S	150S	210S	22.5S	67.5S	112.5S	157.5S	7.5S	22.5S	37.5S	52.5S
22/4	31										7.5F	22.5F	30F	30F	22.5F	30F	30F	30F
27/4	31												7.5F	22.5F		30F	30F	30F
2/5	31															7.5F	30F	30F
7/5	32																22.5F	30F
11/5	33																	37.5F
Total		0	60	120	180	240	60	120	180	240	60	120	180	240	60	120	180	240

S = Urea applied as solid F = Urea applied as foliar spray

7.1.2 Sampling and Analytical Techniques

Grain Yield

The plots were combine harvested on 27 August 1993 using a plot combine and yield adjusted to 85% dry matter.

Statistical Methods

Results were analysed using the Genstat 4 statistical programme. A basic analysis of variance was carried out on all of the data, to obtain the best estimate of the error mean square. The zero N data was then excluded from the analysis and the restricted data set analysed by analysis of variance using the method of orthogonal contrasts (Pearce, 1992), the error mean square from the basic analysis of variance was used in this analysis in calculating the variance ratio. Polynomial contrasts were calculated to determine: averaged over the four forms of N applied, linear and quadratic relationships between the rate of N applied and yield; within the urea treatments, averaged over the four rates of N applied, any linear relationship between the rate of N applied as foliar urea and yield, and any interaction between rate and form. For the purposes of the polynomial contrasts the solid urea was regarded as zero foliar urea. The skeleton analysis of variance for the final analysis is as shown in Table 7.3. All significant differences are quoted at the 5% level.

Table 7.3 Skeleton analysis of variance for the N-rate experiment 1993

Source of Variation	Degrees of freedom
BLOCKS	2
RATE of N APPLIED	3
Linear	1
Quadratic	1
Deviations	1
FORM of N APPLIED	3
Ammonium nitrate v mean of urea treatments	1
Linear foliar urea	1
Deviations	1
RATE x FORM	9
Linear x Ammonium nitrate v mean of urea treatments	1
Quadratic x Ammonium nitrate v mean of urea treatments	1
Deviations x Ammonium nitrate v mean of urea treatments	1
Linear x Linear foliar urea	1
Quadratic x Linear foliar urea	1
Deviations x Linear foliar urea	1
Linear x Deviations foliar urea	1
Quadratic x Deviations foliar urea	1
Deviations	1
Residual (from basic ANOVA)	32

7.1.3 Results

Yield response to nitrogen for the four different forms of N applied is shown in Table 7.4, Figure 7.2. Up to 180 kg N/ha the increase in yield showed a linear response. The response then decreased for 240 kg N/ha applied. On average, over the four forms of N applied, this quadratic trend was significant.

Table 7.4 Yield (t/ha) response to rate of N applied for four forms of N applied in 1993

Form of N applied	Rate of N applied (kg/ha)				
	60	120	180	240	Mean (form)
Ammonium nitrate	7.09	9.04	10.31	10.71	9.29
Solid urea	7.61	8.73	9.89	10.39	9.16
25% foliar urea	7.09	8.79	9.82	10.28	8.99
75% foliar urea	7.23	8.35	9.56	10.17	8.83
Mean (rate)	7.26	8.73	9.90	10.39	
C.V. (%)	4.4				

	Rate	Form	Rate x Form
S.E.M.	0.112	0.112	0.225

On average, over the four rates of N applied, ammonium nitrate significantly increased yield compared to the urea treatments. Differences between the urea treatments were not significant.

There was no significant interaction between rate of N applied and form of application. However, over the range 60-120 kg N/ha, the rate of yield response appeared to be greater for N applied as ammonium nitrate compared to N applied as urea on average, and the linear trend was close to significance.

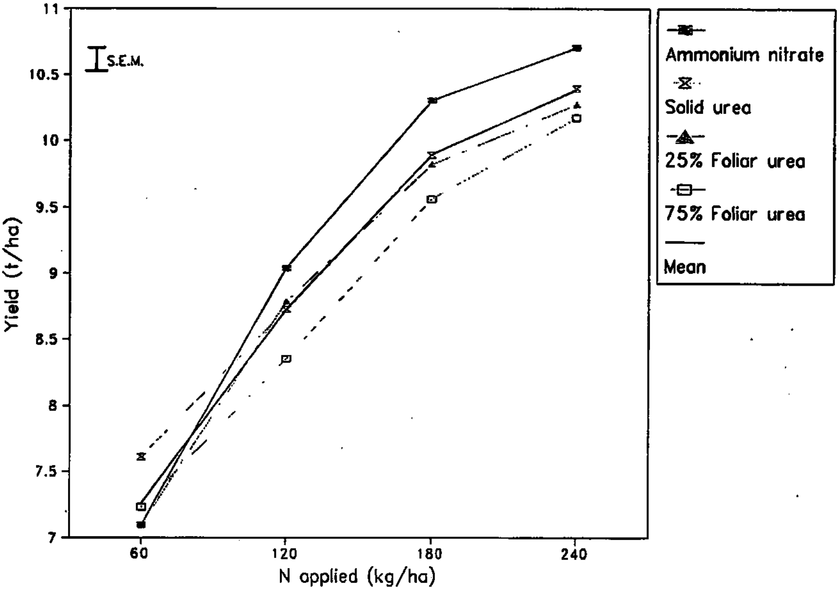


Figure 7.2 Yield response to rate of N applied for four forms of N applied in 1993

7.1.4 Discussion

Yields for the treatments tested in this experiment for 180 kg N/ha applied, were 0.8 - 1 t/ha higher than the corresponding treatments in the main experiment that received 170 kg N/ha. In this experiment, a smaller proportion of the total N was applied in early March around GS 21 compared to the main experiment (30 kg N/ha vs 50 kg N/ha). Spring rainfall was higher than average and the yield difference at harvest could reflect greater losses from the root zone in the main experiment associated with the larger early N application. However, yield from the zero N treatment was also 0.5 t/ha higher than in the main experiment. The increase in yield observed in this experiment may in part at least therefore, be attributable to differences in soil factors between the two sites:

1) Soil mineral N in the spring may have been higher at this site than the main experiment site, due to higher N applications in the previous season: N treated plots in the main experiment received 170 kg N/ha in the previous season, while the N-rate site would have received 215 kg N/ha according to standard farm practice.
2) Soil type at the N-rate site may have been heavier than at the main experiment site, due to increasing clay content of the soil along the field from west to east.
3) Compaction may also have been lower at the site compare to the main experiment site, due to repeated sampling of the main experiment over the experimental period.

In the main experiment, while yield was higher for the ammonium nitrate treatment compared to the urea treatments an average (9.53 t/ha vs 9.22 t/ha), the difference was not significant. In this experiment, averaged over the four rates of N applied, yield was significantly higher for the ammonium nitrate treatment compared to the mean of the urea treatments, and there was an indication from the data that this effect was greater as the rate of N applied increased. The lack of any significant yield difference in the main experiment for ammonium nitrate compared to the mean of the urea treatments may be accounted for due to the higher variability of the data (c.v. = 6.4% vs 4.4%), possibly attributable to greater damage to the plots when sampling the ceramic cups over the winter and conducting growth analysis measurements in the spring and summer. Higher yield response to N as ammonium nitrate compared to urea has been reported by others (Van Burg, 1986; Chaney & Paulson, 1988), and Poulton *et al.* (1990) reported higher grain yield for 160 kg N/ha applied as urea ammonium nitrate mixture to the soil compared to application as foliar urea, though scorch levels were high for the foliar treatments.

While there was a decrease in yield response to N applied between 180 and 240 kg N/ha and on average over the four forms of N applied the quadratic trend was significant as the rate of N applied increased, no clear plateau was evident. Further, the economic optimum is often close to the point of maximum yield (Sylvester-Bradley, 1993); assuming a wheat price of £100/t and a nitrogen cost of 29 p/kg, a yield response of 0.5 t/ha for an extra 60 kg N/ha as recorded in this experiment, still represents an economic response. The data suggests therefore that N-opt for the site in this year was considerably higher than the 170 kg N/ha applied to the main experiment. The application of 170 kg N/ha is based on ADAS recommendations for "other mineral soils", N index zero and anticipated yields of about 7-9 t/ha (MAFF, 1988). As noted earlier (section 3.2.3, Figure 3.6 and 3.7), due to the warm wet spring and summer, yields were higher than expected for the site. The recommended N application for the site given the yield recorded is 230-270 kg N/ha (MAFF, 1994b). This is consistent with the N-rate data. That this experiment indicates an N-opt for the site considerably higher than the 170 kg N/ha applied to the main experiment is therefore attributable to the higher yield potential due to better than average growing conditions this year. The importance of accurate long term weather forecasts in predicting crop N requirements, both from the point of view of behaviour of N in the soil and potential crop demand has been highlighted by other workers, (Prins, Dilz & Neeteson, 1988; Sylvester-Bradley *et al.*, 1984a).

That there was no significant interaction between rate of N applied and form of application is important. Any potential advantage of applying N as foliar urea in terms of reduced N losses must be reproducible over a range of rates of N applied.

7.2 N-RATE EXPERIMENT 1994

In the 1993 N-rate experiment there was no clear indication of N-opt for the site, however, the data indicated that N-opt was in excess of 180 kg N/ha. The experiment was therefore repeated in 1994 and the rates of N used increased to cover the range 150 to 270 kg N/ha. Further, data analysis was extended this year to examine any treatment effects on above ground dry matter production, harvest index and apparent nitrogen recovery.

7.2.1 Field Treatments

The experiment was located some 50 m east of the main experiment site on Little Pipe Strine field, Tibberton Manor Farm, Edgmond. Care was taken to ensure that the experiment was located on ground that had not been used previously for experiments. Crop and establishment details were as given for the main experiment 1994 (section 3.1.1).

Treatments 2, 3, 4, and 6 (solid ammonium nitrate, solid urea, 25% foliar urea and 75% foliar urea) as in the main experiment and as used in the 1993 N-rate experiment were repeated. For each nitrogen treatment N was applied over the range 150 to 270 kg N/ha in equal increments of 40 kg N/ha, to test for any interaction between rate and form of N applied and to identify N-opt for each treatment. In addition, a zero N treatment was included to enable apparent recovery of fertiliser N to be calculated. Nitrogen treatments are summarised in Table 7.5.

As in 1993, the experiment consisted of 51 4 x 10 m plots arranged in three randomised blocks, adjacent blocks separated by a 4 m wheeling (Figure 7.3).

Table 7.5 Nitrogen treatments in the N-rate experiment 1994

Trt. No.	N in early March (kg N/ha)		N at GS 31 (kg N/ha)		Total N (kg/ha)
	Rate	Form	Rate	Form	
1	0	-	0	-	0
2	50	Solid ammonium nitrate	100	Solid ammonium nitrate	150
3	50	Solid ammonium nitrate	140	Solid ammonium nitrate	190
4	50	Solid ammonium nitrate	180	Solid ammonium nitrate	230
5	50	Solid ammonium nitrate	220	Solid ammonium nitrate	270
6	50	Solid urea	100	Solid urea	150
7	50	Solid urea	140	Solid urea	190
8	50	Solid urea	180	Solid urea	230
9	50	Solid urea	220	Solid urea	270
10	50	Solid urea	75 25	Solid urea Foliar urea	150
11	50	Solid urea	105 35	Solid urea Foliar urea	190
12	50	Solid urea	135 45	Solid urea Foliar urea	230
13	50	Solid urea	165 55	Solid urea Foliar urea	270
14	50	Solid urea	25 75	Solid urea Foliar urea	150
15	50	Solid urea	35 105	Solid urea Foliar urea	190
16	50	Solid urea	45 135	Solid urea Foliar urea	230
17	50	Solid urea	55 165	Solid urea Foliar urea	270

14	8	6	10	3	5	4	2	16
13	12	15	9	1	11	7	17	

tramline

5	1	9	16	17	14	3	7	2
6	10	15	12	11	4	13	8	

tramline

13	14	5	8	9	12	11	3	16
17	7	1	10	4	6	2	15	

tramline

Figure 7.3 Plot layout and randomisation for the N-rate experiment 1994 (numbers refer to treatments, refer to Table 7.3)

All treatments except the zero N treatment received 50 kg N/ha in early March. Solid ammonium nitrate (Nitram 34.5% w/w) and solid urea (Seabright 46% w/w) were applied to the plots by hand. Foliar urea was applied as Nufol (20% w/v; NUFOL, Hydro Chafer Ltd., York) diluted with water to give a constant application volume of 300 l/ha. For those treatments receiving > 40 kg N/ha as foliar urea, the objective was to apply 30 kg N/ha every 4 to 5 days starting at GS 31 and a final "balance application" to give the required rate of N as foliar urea according to treatment. For those treatments receiving < 40 kg N/ha as foliar urea, the full rate of N was applied as a single application. Actual dates and growth stages of application are given in Table 7.6. Foliar applications were not made to wet leaves or when rain was imminent. All foliar urea applications were made through flat fan nozzles using an Oxford precision sprayer, as for the main experiment.

Table 7.6 Dates of N applied in the N-rate experiment 1994

		TREATMENT																
Date Applied	ZGS	Zero-N	NH_4NO_3 (kg N/ha)				Solid urea (kg N/ha)				25% Foliar urea (kg N/ha)				75% Foliar urea (kg N/ha)			
			150	190	230	270	150	190	230	270	150	190	230	270	150	190	230	270
12/3	22		50	50	50	50	50S	50S	50S	50S	50S	50S	50S	50S	50S	50S	50S	50S
24/4	30/31		100	140	180	220	100S	140S	180S	220S	75S	105S	135S	165S	25S	35S	45S	55S
20/4	30/31										25F	35F	30F	30F	30F	30F	30F	30F
28/4	31												15F	25F	30F	30F	30F	30F
2/5	31														15F	30F	30F	30F
6/5	32															15F	30F	30F
12/5	33																15F	30F
17/5	33																	15F
Total		0	150	190	230	270	150	190	230	270	150	190	230	270	150	190	230	270

S = Urea applied as solid   F = Urea applied as foliar spray

7.2.2 Sampling and Analytical Techniques

Above Ground Dry Matter at Harvest

On the 9 August, plants from two adjacent 0.5 m lengths of row were cut at soil level from four positions in each plot. The samples were bulked and dried at 80 °C for 48 hours. Total above ground dry matter was calculated using row width to determine sampling area.

Above Ground Plant N

20 whole plant stems were randomly selected from the dried bulk sample and above ground plant N determined. Details of the analysis were as given for the main experiment 1992 (section 3.1.2). Apparent recovery of fertiliser N in the above ground plant dry matter was calculated for each plot.

Grain Yield

The plots were combine harvested on 15 August 1994 using a plot combine and yield adjusted to 85% dry matter.

Statistical Methods

Statistical analysis was as given for the 1993 N-rate experiment (section 7.1.2). The skeleton analysis of variance is as shown in Table 7.7. All significant differences are quoted at the 5% level.

Table 7.7 Skeleton analysis of variance for the N-rate experiment 1994

Source of Variation	Degrees of freedom	
	Apparent N recovery	All other analyses
BLOCKS	2	2
RATE of N APPLIED	3	3
Linear	1	1
Quadratic	1	1
Deviations	1	1
FORM of N APPLIED	3	3
Ammonium nitrate v mean of urea treatments	1	1
Linear foliar urea	1	1
Deviations	1	1
RATE x FORM	9	9
Linear x Ammonium nitrate v mean of urea treatments	1	1
Quadratic x Ammonium nitrate v mean of urea treatments	1	1
Deviations x Ammonium nitrate v mean of urea treatments	1	1
Linear x Linear foliar urea	1	1
Quadratic x Linear foliar urea	1	1
Deviations x Linear foliar urea	1	1
Linear x Deviations foliar urea	1	1
Quadratic x Deviations foliar urea	1	1
Deviations	1	1
Residual (from basic ANOVA)	30	32

7.2.3 Results

Yield, Above Ground Dry Matter and Harvest Index (Table 7.8-7.10, Figure 7.4-7.6)

On average over the four forms of N applied, yield increased significantly in a linear manner as the rate of N increased from 150 to 270 kg N/ha. On average over the four rates of N applied, form of N had no significant effect on yield. There was no significant interaction between rate and form with respect to yield.

With respect to above ground dry matter production and harvest index, there was no significant effect of rate of N applied on average over the four forms, or form of N applied on average over the four rates of N applied. There was an indication from the data that above ground dry matter production on average over the four forms of N applied increased with rate of N applied, however, this was not significant. There was no significant interaction between rate and form.

Table 7.8 Yield response (t/ha) to rate of N applied for four forms of N applied in 1994

Form of N applied	Rate of N applied (kg/ha)				
	150	190	230	270	Mean (form)
Ammonium nitrate	6.698	7.073	6.910	7.381	7.016
Solid urea	6.128	7.018	6.760	6.870	6.964
25% foliar urea	6.337	7.155	6.896	7.606	6.998
75% foliar urea	6.450	6.607	7.160	7.069	6.821
Mean (rate)	6.403	6.963	6.931	7.232	
C.V. (%)	7.5				

	Rate	Form	Rate x Form
S.E.M.	0.1451	0.1451	0.2902

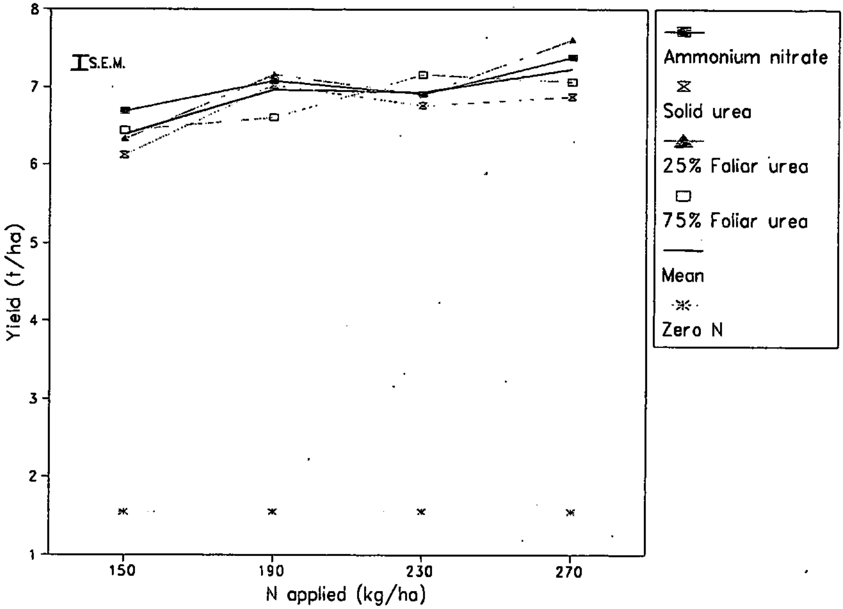


Figure 7.4 Yield response to rate of N applied for four forms of N applied in 1994

Table 7.9 Above ground dry matter (t/ha) response to rate of N applied for four forms of N applied in 1994

Form of N applied	Rate of N applied (kg/ha)				
	150	190	230	270	Mean (form)
Ammonium nitrate	11.70	11.60	12.40	12.93	12.16
Solid urea	11.29	11.79	11.25	12.60	11.73
25% foliar urea	12.25	13.28	12.41	12.62	12.64
75% foliar urea	10.90	12.20	11.69	12.47	11.81
Mean (rate)	11.54	12.22	11.94	12.66	
C.V. (%)	10.9				

	Rate	Form	Rate x Form
S.E.M.	0.377	0.377	0.754

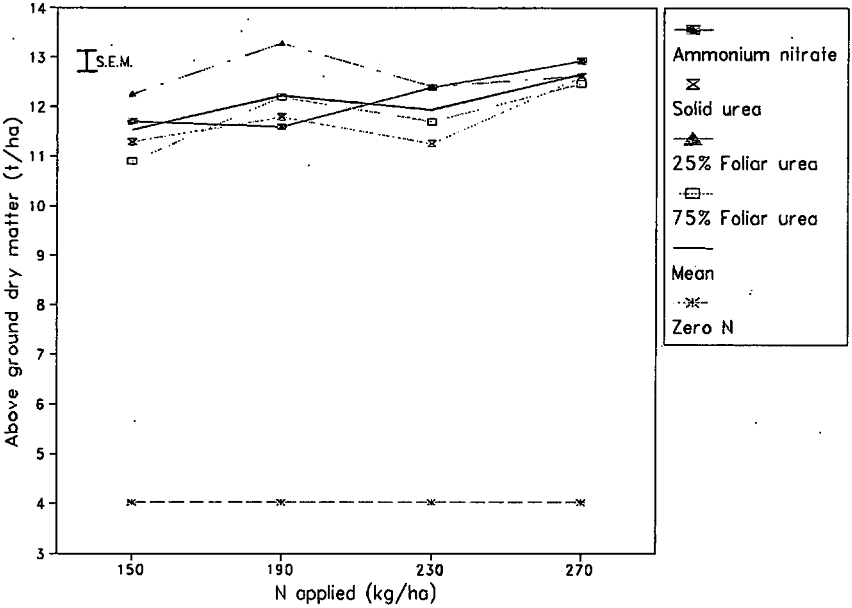


Figure 7.5 Above ground dry matter response to rate of N applied for four forms of N applied in 1994

Table 7.10 Harvest index response to rate of N applied for four forms of N applied in 1994

Form of N applied	Rate of N applied (kg/ha)				
	150	190	230	270	Mean (form)
Ammonium nitrate	0.5799	0.6111	0.5575	0.5692	0.5794
Solid urea	0.5523	0.5956	0.6037	0.5461	0.5744
25% foliar urea	0.5385	0.5413	0.5600	0.6053	0.5613
75% foliar urea	0.5940	0.5422	0.6124	0.5658	0.5786
Mean (rate)	0.5662	0.5726	0.5834	0.5716	
C.V. (%)	9.5				

	Rate	Form	Rate x Form
S.E.M.	0.01615	0.01615	0.03230

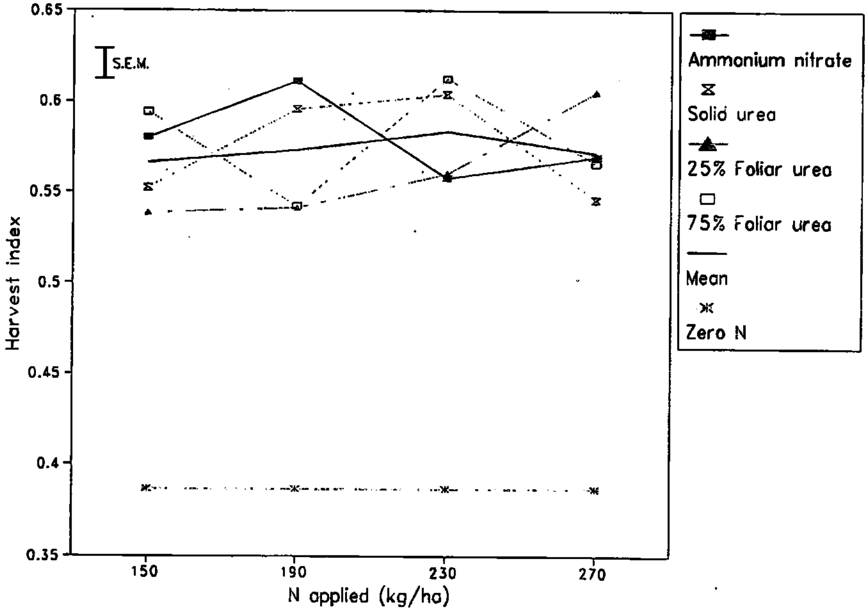


Figure 7.6 Harvest index response to rate of N applied for four forms of N applied in 1994

N Content (N%) and Above Ground Plant N (kg/ha in the dry matter) (Table 7.11 & 7.12, Figure 7.7 & 7.8)

On average over the four forms of N applied, there was a significant quadratic increase in N content of the above ground dry matter and a significant linear increase in total above ground N with N rate. On average over the four rates of N applied, ammonium nitrate significantly increased N content and total above ground plant N compared to N applied as urea on average, differences between the urea treatments were not significant.

N content of the above ground dry matter showed a significant quadratic interaction between rate and form for N applied as ammonium nitrate compared to N applied as urea on average: over the lower rates of N tested the increase in N content with rate of N applied was higher for the ammonium nitrate compared to urea on average, however, at the higher rates of N tested the response was lower for ammonium nitrate compared to urea on average. There was no significant interaction between rate and form for above ground plant N. The interaction between rate and form for N content for ammonium nitrate compared to the urea treatments on average, as above, was compensated for by differences in above ground dry matter production in this respect.

Apparent N Recovery (Table 7.13, Figure 7.9)

On average over the four forms of N applied, apparent recovery of fertiliser N in the above ground crop showed a significant linear decrease as the rate of N applied increased. On average over the four rates of N applied, form of N had no significant effect on apparent N recovery. There was no significant interaction between rate and form with respect to apparent N recovery.

Table 7.11 N content of the dry matter (N%) with N rate for four forms of N applied in 1994

Form of N applied	Rate of N applied (kg/ha)				
	150	190	230	270	Mean (form)
Ammonium nitrate	0.998	1.458	1.504	1.490	1.362
Solid urea	1.126	1.319	1.300	1.355	1.275
25% foliar urea	1.102	1.194	1.343	1.432	1.268
75% foliar urea	1.114	1.171	1.296	1.395	1.244
Mean (rate)	1.085	1.286	1.361	1.418	
C.V. (%)	8.6				

	Rate	Form	Rate x Form
S.E.M.	0.0313	0.0313	0.0626

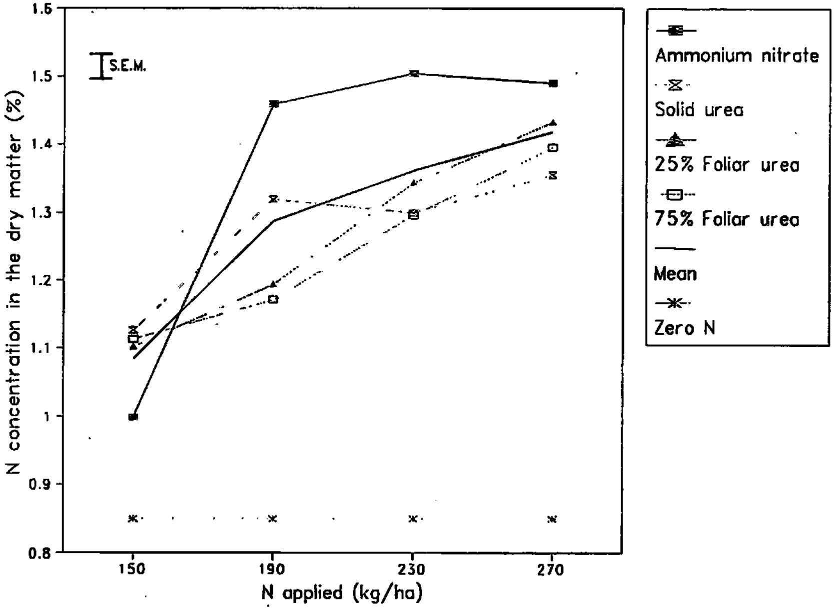


Figure 7.7 N content of above ground dry matter with N rate for four forms of N applied in 1994

Table 7.12 Above ground plant N (kg/ha) with N rate for four forms of N applied in 1994

Form of N applied	Rate of N applied (kg/ha)				
	150	190	230	270	Mean (form)
Ammonium nitrate	119.5	167.5	186.0	192.5	166.4
Solid urea	126.4	155.4	145.1	170.9	149.5
25% foliar urea	133.3	158.3	168.0	179.7	159.8
75% foliar urea	121.6	142.8	151.2	173.6	147.3
Mean (rate)	125.2	156.0	162.6	179.2	
C.V. (%)	12.2				

	Rate	Form	Rate x Form
S.E.M.	5.38	5.38	10.75

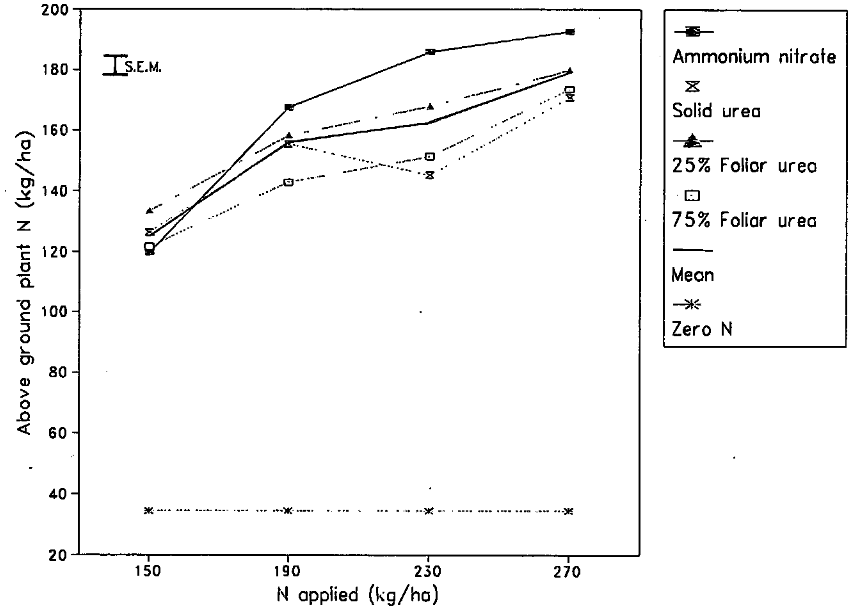


Figure 7.8 Above ground plant N with N rate for four forms of N applied in 1994

Table 7.13 Apparent recovery of fertiliser N (%) in the above ground dry matter with N rate for four forms of N applied in 1994

Form of N applied	Rate of N applied (kg/ha)				
	150	190	230	270	Mean (form)
Ammonium nitrate	56.9	70.1	66.0	58.6	62.9
Solid urea	61.5	63.8	48.2	50.6	56.0
25% foliar urea	66.0	65.3	58.1	53.9	60.8
75% foliar urea	58.2	57.1	50.8	51.6	54.5
Mean (rate)	60.6	64.1	55.8	53.7	
C.V. (%)	18.4				

	Rate	Form	Rate x Form
S.E.M.	3.11	3.11	6.22

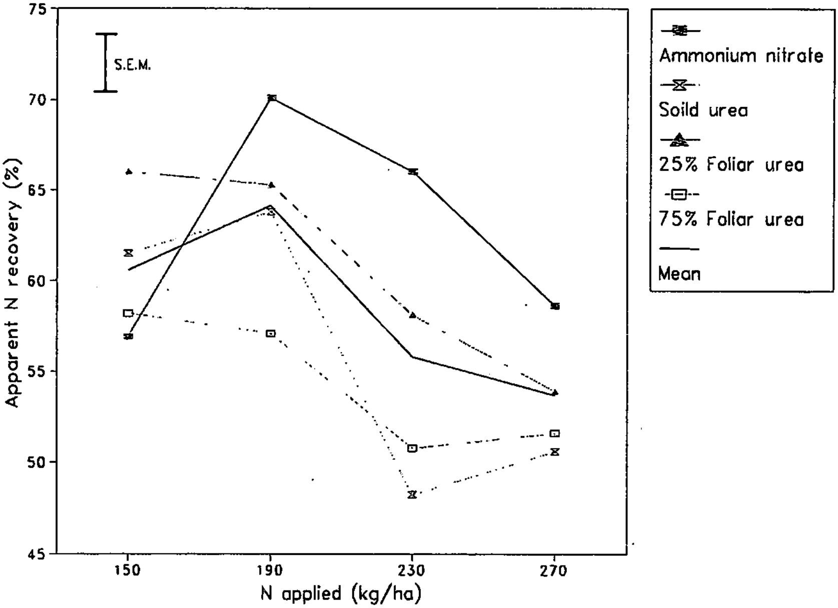


Figure 7.9 Apparent recovery of fertiliser N in the above ground plant dry matter with N rate for four forms of N applied in 1994

7.2.4 Discussion

Yield, Above Ground Dry Matter and Harvest Index

Yields for 150 and 190 kg N/ha applied in this experiment were higher than for the corresponding treatments in the main experiment receiving 170 kg N/ha. Extrapolation between the two rates indicates that yield for 170 kg N/ha in this experiment would have been 0.3-0.5 t/ha higher than in the main experiment. Further, yield for the zero N treatment was 0.6 t/ha higher in this experiment.

Higher yields for corresponding treatments in the N-rate experiment compared to the main experiment were also recorded in 1993. It was suggested that this may have been attributable to reduced leaching of the early N applied in the N-rate experiment, associated with a smaller proportion of the total N applied in early March compared to the main experiment and / or a number of soil factors including; higher soil mineral N in the spring, change in soil type and reduced compaction for the N-rate site. This year, early N applied was the same for both experiments (50 kg N/ha in early March), however, as in 1993, the N-rate site would have received 215 kg N/ha in the previous year (standard farm practice), while the main experiment site would have received 170 kg N/ha. Change in soil type would have been more marked this year due to the experiment being located further east along the field, and the influence of soil type would also have been expected to have been more pronounced due to the hot dry growing season this year compared to 1993. As in 1993, soil compaction at the N-rate site would have been expected to be less than at the main site, due to reduced sampling. The indication therefore, is that one or more of these soil factors is responsible for the higher yield recorded at the N-rate site compared to the main experiment.

The yield data in this experiment does not follow the pattern of diminishing returns typical of N response curves (George, 1984). The yield response in this experiment is more typical of the "plateau region" of the response curve. This can be attributed to the limited yield potential of the site due to poor growing conditions this year, in particular lower than average rainfall, such that the yield response over the rates of N applied was limited (0.8 t/ha for 120 kg N/ha applied - average yield response over four forms of N tested).

The recommended N application for the site, given the average yield recorded (6.9 t/ha) is 190 kg N/ha (MAFF, 1994b). Due to the limited response over the range of rates tested N-opt can not be determined, however, assuming a wheat price of £100/t and a nitrogen cost of 29 p/kg, an extra 0.8 t/ha of grain for 120 kg N/ha applied still represents an economic response.

On average over the four forms of N applied, the significant linear increase in yield with rate of N applied can be related to the increase in above ground dry matter production, though this was not significant. Differences in harvest index, on average over the four forms of N applied, were small and a decrease in harvest index was evident at the highest rate of N applied. The effects of N rate on above ground dry matter production and harvest index as recorded here are in accordance with observations reported elsewhere (Donald and Hamblin, 1976; Hay, 1995).

The lack of any significant interaction with respect to grain yield between rate and form of N applied, supports the results from the 1993 N-rate experiment and indicates that the yield response to N applied as foliar urea is reproducible over a range of rates of N applied.

Above Ground Plant N and Apparent N Recovery

On average over the four forms of N applied, the quadratic increase in N content (N%) of the above ground dry matter with rate of N applied, largely reflects the trend for the ammonium nitrate and solid urea treatments. The foliar urea treatments showed an almost linear increase up to 270 kg N/ha. On average over the four rates of N applied, the significantly higher N content for the ammonium nitrate treatment compared to the urea treatments on average, is in contrast to the effect of extra N applied as ammonium nitrate at GS 32 or as foliar urea applied at GS 75 on grain N content, as reported by Cross (1992).

The significant linear increase in above ground plant N, on average over the four forms of N applied, with rate of N applied, reflects the quadratic increase in N content of the plant material and the (non significant) increase in above ground dry matter. On average over the four rates of N applied, the significantly higher above ground N for the ammonium nitrate treatment compared to the urea treatments on average is due to the significantly higher N content of the dry matter, above ground dry matter production was not significantly different for the ammonium nitrate treatment and the urea treatments on average.

As the rate of N increased, the linear decrease in apparent N recovery, on average over the four forms of N applied, was as expected and reflects the quadratic trend in above ground plant N. Apparent recovery of fertiliser N in the grain, as calculated from mean data for eight sites reported by Chaney (1990), showed a similar decrease for N applications above the economic optimum. The significantly higher above ground N (kg/ha) for the ammonium nitrate treatment, on average over the four rates of N applied, compared to the urea treatments on average, was not reflected in apparent recovery of fertiliser N in the above ground crop. This can be related to the higher variability of the apparent N recovery data compared to the above ground N data (c.v. = 18.4% vs 12.2%). Cross (1992) has reported inconsistent effects on apparent N recovery for extra N applied as ammonium nitrate at GS 32 compared to foliar urea applied at GS 75.

8.0 GENERAL DISCUSSION AND CONCLUSION

In the previous sections the results of each of the experiments in this study have been discussed comprehensively, in their own right, and in relation to other experiments carried out in this study and by other workers. The objective of this section is to draw together the main points arising from these discussions, and to set them in their wider context.

8.1 Effects of Foliar Urea on Crop Growth and Yield

Application of N as foliar urea to reduce N losses is attractive: supplying a proportion of the total fertiliser N requirement through the foliage would potentially reduce immobilisation of fertiliser N in the soil organic matter and / or losses by leaching or denitrification. Clearly, however, any novel agronomic practice to reduce N losses must be at least able to maintain the yield efficiency currently achieved with conventional agronomic practice. A principle objective of this study was to compare yield for N applied conventionally to the soil as solid ammonium nitrate or urea and as different proportions of foliar urea, and to determine the physiological basis for any yield differences.

Few studies have been found in the literature where foliar urea has been used to replace the main N application conventionally applied to the soil around GS 32: Poulton *et al.* (1990) recorded a reduction in grain yield for repeated urea sprays (40 kg N/ha x 4) applied between GS 32 and 51, compared with 160 kg N/ha applied to the soil as urea ammonium nitrate mixture at GS 32. However, Kettlewell and Juggins (1992) have reported no significant difference in yield for 125 kg N/ha applied as solid ammonium nitrate or as a number of foliar urea sprays between GS 32 and 37, though there was an indication that foliar urea may have reduced yield for foliar urea treatments receiving the largest quantities of N in any one application, and Warden and Kettlewell (1993) found no reduction in yield for up to 210 kg N/ha applied as foliar urea at GS 32. In the study reported in this thesis, in two out of three years of the main experiment, there was no indication that application of N as foliar urea reduced yield compared to N applied conventionally to the soil as solid ammonium nitrate or urea. In 1994, there was evidence of a reduction in yield for the treatment receiving all of its N as foliar urea, however, this was associated with implied gaseous losses of the early 50 kg N/ha applied around GS 21, due to application under conditions that are likely to have been conducive to losses by volatilisation and / or denitrification. In the ^{15}N label, N-timing and interception experiments, there was no significant difference in yield for N applied as foliar urea compared with N applied as solid ammonium nitrate or urea. In the N-rate experiments conducted in 1993 and 1994, there was no significant effect on yield as the rate of N applied as foliar urea increased and no significant interaction between rate of N applied and proportion of N as foliar urea, indicating that the yield response to N applied as foliar urea is reproducible over a range of rates of N applied. The data recorded from a number of experiments in this study therefore indicates, that N applied as foliar urea can produce similar yields to N applied conventionally to the soil as solid ammonium nitrate or urea, and that the yield response is reproducible over a range of rates of N applied.

The yield reduction reported by Poulton *et al.* (1990) for N applied as foliar urea, may have been attributable to leaf scorch and / or differences in timing of application of N in relation to plant development: a single rate of foliar urea was applied at a relatively high N concentration, to a well developed crop and leaf scorch, possibly exacerbated by the use of a wetting agent, was observed. Timing of N application in relation to the development of the leaf canopy and yield components is likely to be critical with respect to yield. Applications of foliar urea in this study, even in 1992 when application was delayed due to inclement weather, were considerably earlier than reported by Poulton *et al.*. The yield reduction recorded by Poulton *et al.* (1990), may have resulted from reduced effectiveness due to late application: foliar urea applications were made between 9 May and 18 June, corresponding to GS 31 to 51. The degree of scorch following application of foliar urea in the study reported in this thesis was also very low, less than 5 % in all cases. Warden and Kettlewell (1993) have reported no significant effect on yield for levels of scorch up to 17% for foliar urea applications at GS 32, and Dampney and Salmon (1990) have reported no significant effect on yield for levels of scorch less than 10% due to foliar urea applied over a range of later timings (GS 39-90).

Grain yield is a function of above ground dry matter production and harvest index, the proportion of the dry matter partitioned to the grain. The results from the main experiment over the 3 years, indicate that foliar urea maintains yield by influencing both above ground dry matter production and harvest index, and that it appears to be compensatory in these two effects; an increase in above ground dry matter production being offset by a decrease in harvest index and *vice versa*, such that yield is maintained. Further, the results suggest that the balance between the effect on above ground dry matter production and harvest index is determined by time of application in relation to stage of plant development. In 1993 and 1994 when, due to a"tight" spray programme, <u>all</u> foliar urea sprays were applied relatively early, around GS 32, where the rate of N applied as foliar urea was relatively low, and therefore a larger proportion of the total N was applied early, above ground dry matter production was increased but a smaller proportion of the dry matter was partitioned to the grain (reduced harvest index). For those treatments receiving a higher rate of N as foliar urea (120 and 170 kg N/ha as foliar urea) and therefore that received a proportion of the total N later, above ground dry matter production was reduced, but the dry matter was partitioned more efficiently to the grain (increased harvest index) and yield was maintained. In 1992 due to bad weather, application of foliar urea sprays was delayed compared to 1993 and 1994. Consequently, even those treatments receiving a smaller proportion of N as foliar urea, received a relatively late application of foliar urea compared to 1993 and 1994. The effect of delayed application was to reduce the above ground dry matter production and increase harvest index, even for those treatments receiving a relatively small proportion of total N as foliar urea. This compensatory effect of foliar urea on the components of grain yield according to time of application, reflects the general view, that within limits, time of application has less effect on grain yield than the amount of N applied (Needham, 1984), and may account for the limited success of very precise timing of N application to coincide with certain critical stages of plant development, in increasing grain yield (Sylvester-Bradley *et al.*, 1987).

The objective of the N timing experiment conducted in 1993 was to determine, for selected treatments in the main experiment, whether effects on above ground dry matter production and harvest index in the main experiment were due to rate of N applied as foliar urea or, as postulated, time of application of N in relation to crop development. Limited differences in time of application for N applied as per the main experiment and all at GS 31 and limited uptake of fertiliser N in this experiment, possibly compounded by disease and lodging effects at the site, may account for the lack of any evidence in this experiment to support the hypothesis, that the physiological response of winter wheat to foliar urea is due to compensatory effects on above ground dry matter production and harvest index according to time of application.

The growth analysis data for the main experiment in 1993 and 1994, indicates that the effect of foliar urea on above ground dry matter production at harvest is due to effects on green area index at anthesis. In both years, the trend in above ground dry matter production at harvest showed a close correlation with green area index around anthesis. Gallagher and Biscoe (1978a), have demonstrated the strong correlation between the rate of dry matter production and intercepted radiation, the latter being a function of incident radiation and green area index (Monsi and Saeki, 1953). The light interception data recorded in 1994, confirmed that differences in green area index between treatments were reflected by differences in intercepted radiation.

The growth analysis and shoot count data further indicate, that the effect of foliar urea on green area index is due to foliar N affecting the size of the green components: the trend in green area index at anthesis in both years was closely correlated with the trend in stem and leaf area index. The effect of N on leaf area index is well documented, N does not affect the rate of leaf initiation and appearance or number of leaves on individual main stems or tillers, but it increases the size of individual leaves (Puckeridge, 1963; Milthorpe & Moorby, 1979; Biscoe & Gallagher, 1978; Willington & Biscoe, 1984; Sylvester-Bradley *et al.*, 1990b; Sylvester-Bradley & Scott, 1990). Consideration of the flag leaf green area over the last two growth analyses in 1993, showed that the reduction in flag leaf green area was similar over the urea treatments, the implication being that the effect of foliar N on leaf size is due to effects on leaf expansion rather than leaf persistence. Further, consideration of data for individual leaves down the stem in 1994, showed that the trend in leaf area index and leaf dry weight as the rate of N applied as foliar urea increased, was largely a reflection of differences in leaf area index and leaf dry weight for those leaves that were calculated to have been expanding at the time of N application. The effect of N on leaf size by increasing the rate of leaf expansion has been reported by others (Gallagher, 1976; Biscoe and Gallagher, 1978; Sylvester-Bradley and Scott, 1990), and Sylvester-Bradley *et al.* (1990b), have implied that this may be due to a direct effect of increased water content of the tissues, associated with increased N uptake, causing tissues to expand.

The implication therefore, is that the effect of foliar urea on above ground dry matter production is due to effects on green area index (and intercepted radiation), due to foliar urea affecting the rate of expansion of those leaves developing at the time of application. An effect on stem growth was also indicated. Sylvester-Bradley *et al.* (1990b) have suggested that the size of a crop's canopy is directly proportional to the amount of N it has been able to acquire, for cereals about 30 kg N being required to produce 1 hectare of green surface.

Harvest index is the ratio of grain yield to above ground dry matter production. The proportion of dry matter partitioned to the grain is a function of shoots bearing ears at harvest and ear development in terms of spikelet and floret formation, spikelet and floret survival and grain filling. As discussed, from the results of the main experiment, the effect of foliar urea on harvest index appeared to be related to time of application of the foliar urea sprays. The largest effect on harvest index was recorded in the first year when foliar urea applications were delayed. In subsequent years, due to earlier application of foliar urea sprays, the increase in harvest index was more limited and only evident for those treatments receiving a larger proportion of N as foliar urea and therefore that would have received a proportion of their N later. The start of floret death in winter wheat, as reported in the literature, ranges from GS 32-39 (Gallagher and Biscoe 1978b; Baker and Gallagher, 1983; Barling, 1982). Given the lack of any effect of foliar urea on shoot production, and due to the apparent timing effect of foliar urea on harvest index, it was proposed that the effect of foliar urea on harvest index was due to N offsetting floret death. The increase in grains per fertile spikelet recorded for N applied from floret initiation to ear emergence (Single, 1964; Langer and Liew, 1973; Darwinkel, 1983) together with the lack of any effect of N on floret production (Langer and Hanif, 1973; Whingwiri and Stern, 1982), and therefore the implied effect of N in reducing floret abortion, was noted in the literature review. Further, Peltonen (1992) has reported a maximum increase in fertile florets per ear for foliar urea applied around GS 39 when the number of florets initiated is maximal. Grains per ear and grain yield were also increased, however, total above ground dry matter production increased proportionally and no effect on harvest index was evident. A number of other workers have reported an increase in grains per ear for N applied as foliar urea over a range of timings from the end of tillering to anthesis (Sadaphal and Das, 1966; Arnold and Dilz, 1967; Strong, 1982, Lawlor *et al.*, 1989; Sarandon and Gianibelli, 1990), in some of these the increase in grain yield and above ground dry matter was disproportionate, and harvest index increased (Sadaphal and Das, 1966; Sarandon and Gianibelli, 1990).

The objective of the harvest growth analysis in the main experiment in 1994, was to establish the basis of the physiological effect of foliar urea on harvest index. That no evidence was found to support the hypothesis that the effect of foliar urea on harvest index was due to N offsetting floret death, is likely to be related to the limited difference in time of application of foliar N in this experiment; as already noted the largest effect of N applied as foliar urea was evident in the first year, when foliar urea sprays were applied relatively late due to bad weather. The rate of floret death increases, reaching a peak in the three weeks prior to anthesis (Gallagher and Biscoe, 1978b). It is logical to expect therefore, that later applications of foliar N are likely to be more effective at offsetting floret death.

Given the large proportion of "foliar" urea reaching the soil surface as indicated by the spray interception data, the physiological effects of "foliar" urea on above ground dry matter production and harvest index according to time of application as discussed, could have resulted from delayed uptake of N from urea in the soil due to restricted hydrolysis, rather than a direct effect of time of application. This possibility cannot be excluded.

The full importance of the likely effect of time of application in determining the effect of foliar N on above ground dry matter and harvest index, was not apparent until after the analysis of the second year data. The logistical problems of analysing and interpreting the substantial amount of data generated, between harvesting one crop and N application to the next crop in the following spring, prevented full recognition of this phenomenon in time to actively delay applications of foliar urea in the final year.

Recently a novel strategy for N fertiliser application to winter cereals has been developed, referred to as "canopy management" (Sylvester-Bradley and Kettlewell, 1995). This involves applying a lower amount of total N, but as a number of applications, such that N is applied on average later. The objective being to achieve a smaller canopy (target GAI = 5), but to maintain the canopy for longer. Foliar urea sprays have been used for later applications under dry conditions in this respect. Crops under canopy management are reported to have fewer shoots than normal, but more grains per ear and the grains may be larger. The effects of canopy management reflect the effects of foliar urea on dry matter production and harvest index as identified here.

In conclusion, with respect to effects on crop growth and yield, the results from the series of experiments in this study indicate that N applied as foliar urea can produce similar yields to N applied conventionally to the soil as ammonium nitrate or urea, over a range of rates of N applied. Foliar urea appears to maintain yield by affecting both above ground dry matter production and harvest index according to time of application in relation to plant development, and it appears to be compensatory in these effects: early application of foliar urea increases above ground dry matter production but has little effect on harvest index, while later applications reduce above ground dry matter production and increase harvest index. Effects on above ground dry matter production can be related to green area index around anthesis, primarily due to foliar N affecting the expansion of those leaves developing at the time of application. It is postulated that the effect of late applications of foliar urea on harvest index are due to foliar N offsetting floret death. The results of harvest growth analysis to support this were, however, inconclusive.

8.2 Effects of Foliar Urea on N Recovery and N Losses from the Crop-Soil System

A second objective of this work was to investigate the effect on nitrate leaching of supplying N as foliar urea rather than as conventional solid ammonium nitrate or urea applied to the soil. Clearly, however, as highlighted by Addiscott *et al.* (1991), it is important that any changes to agricultural practice designed to reduce nitrate leaching do not lead to an increase in N losses by other pathways such as denitrification or volatilisation.

In the experiment of Poulton *et al.* (1990), lower overall recovery of fertiliser N in the crop plus soil for N applied as foliar urea was recorded, and volatilisation losses from the foliar applied urea were implicated. Bowman and Paul (1987 & 1990b) have suggested volatilisation as the likely cause of N losses from foliar urea applied to Kentucky blue grass turf, and volatilisation has also been implicated as the principle cause of loss from late N applications of foliar urea to boost grain protein in wheat (Powlson *et al.*, 1989a; Powlson *et al.*, 1987a).

In the main experiment in 1992, reduced apparent N recovery in the above ground crop and reduced soil mineral N in the autumn, particularly for the all foliar urea treatment, indicated gaseous losses and/or immobilisation of fertiliser N as the rate of N applied as foliar urea increased. Due to the effects of temperature and windspeed on ammonia volatilisation and denitrification (Haynes and Sherlock, 1986), application of the foliar urea sprays early in the day followed by warm windy conditions, would have favoured the former. Alternatively, the significant increase in the C/N ratio of the straw + chaff fraction as the rate of N applied as foliar urea increased, would have favoured an increase in fertiliser N removed from the plant-soil mineral N system by immobilisation in the autumn (Powlson, 1993). In 1993, the lack of any significant decrease in apparent N recovery and soil mineral N in the autumn as the rate of

N applied as foliar urea increased, was attributed to application of foliar urea sprays in the evening rather than during the day, and earlier application of the main N in cooler conditions, due to a "tighter" spray programme. Both of these effects would have been less conducive to gaseous losses compared to 1992. The results from the main experiment in 1992 and 1993 therefore indicate that if foliar urea is applied under appropriate conditions, gaseous losses of N can occur and that these can be important at high rates of N applied.

Further evidence to support this hypothesis was provided from the 1994 data. A decrease in apparent N recovery recorded for the all foliar urea treatment in the main experiment and the interception experiment, was related to application of the early 50 kg N/ha to these treatments early in the day, as in 1992. Reduced shoot production up to anthesis, indicating reduced uptake of early N by the plant (Biscoe, 1979; Langer, 1980; Darwinkel, 1983; Sylvester-Bradley and Scott, 1990), recorded for the all foliar urea treatment in the main experiment, further supports this.

The hypothesis that gaseous losses can be important for N applied as foliar urea under conditions conducive to volatilisation and/or denitrification, is logical. However, immobilisation of fertiliser N in the soil organic matter cannot be excluded. The objective of the ^{15}N experiment carried out in 1993, was to account for any differences in immobilisation between treatments as the rate of N applied as foliar urea increased. No significant difference in true recovery of fertiliser N in the plant and soil (mineral + organic fractions) was recorded. That no evidence was found in this experiment to support the hypothesis regarding gaseous losses, is likely to have been due to application of foliar urea sprays in this experiment, as in the main experiment in 1993, under conditions that would limit the potential for volatilisation and/or denitrification: application in the evening and a "tight" spray programme ensuring application of all foliar urea sprays relatively early, under cooler conditions. Total recovery (true) of ^{15}N labelled fertiliser N in this experiment was similar for N applied as solid ammonium nitrate or urea to the soil and for N applied as foliar urea. If it is assumed that the mineralisation/immobilisation balance for fertiliser N in the soil following application was similar this year as in other years, then the implication is that the lower apparent N recovery of fertiliser N in the plant-soil mineral N system recorded in 1992 as the rate of N applied as foliar urea increased, and evident for the all foliar urea treatment in 1994, is likely to have been due to higher gaseous losses. Consideration of the details regarding time of application of foliar urea sprays in the experiment reported by Poulton *et al.* (1990), shows that foliar urea applications were made between 9 May and 18 June, corresponding to GS 31-51. Compared to the ^{15}N experiment reported here, foliar urea applications were therefore made relatively late, under conditions that were likely to have been more conducive to gaseous losses.

The most likely cause of N loss from urea falling on the foliage would have been volatilisation as the urea was hydrolysed (Powlson *et al.*, 1987a; Poulton *et al.*, 1990). That falling on the soil surface would have been subject to volatilisation losses and after conversion to nitrate, losses by denitrification or leaching. Poulton *et al.* (1990) implied volatilisation from foliar intercepted urea as the likely cause of loss in their experiment. The interception experiment carried out in this study in 1994, indicated that of the "foliar" urea applied around GS 31, a maximum of 35% was intercepted by the foliage and for the early 50 kg N/ha applied around GS 21, only 6 to 9% was intercepted by the foliage. In the experiment of Poulton *et al.* (1990) foliar urea applications were made later to a more advanced crop, and it is likely that foliar interception would have been higher. Given the large proportion of "foliar" urea falling on the soil recorded in this study, however, the potential for gaseous losses by denitrification cannot be ignored. Addiscott and Powlson (1992), have indicated the importance of N losses by denitrification for nitrogen applied to winter cereals. Denitrification tends to be favoured by anaerobic conditions created due to wetness (Fillery, 1983; Sahrawat and Keeney, 1986). Therefore, while denitrification cannot be ruled out, it is likely that the soil conditions prevailing at the time of "foliar" urea application would have been more conducive to gaseous losses by volatilisation.

The assumption that urea is hydrolysed to NH_4^+ is implicit in the hypothesis that gaseous losses can be important for N applied as foliar urea. Urea hydrolysis requires water, and rapid volatilization from urea only occurs when the volatilising surface is moist (Volk, 1966; Mahli and Nyborg, 1979; Fergusson and Kissel, 1986). Consequently, conditions conducive to ammonia volatilisation, may reduce volatilisation from urea by drying the volatilising surface and inhibiting urea hydrolysis (Fergusson and Kissel, 1986). While this is accepted, it is considered that ammonia volatilisation from foliar urea is likely to be dependant upon the characteristics of the microenvironment at the site of fertiliser application. Hauck (1984), has noted the dependence of ammonia volatilisation from urea applied to the soil, on the characteristics of the soil microsite adjacent to the urea particle. Moisture retained within the canopy at this time of year, even under warm windy conditions that promote rapid drying of the upper leaves, is likely to be sufficient to allow continued hydrolysis of urea by urease. Hargrove *et al.* (1977) have reported that the moisture from dewfall can be sufficient to significantly stimulate ammonia volatilisation from ammonium sulphate applied to dry calcareous soils, and Reynolds and Wolf (1987) have reported that humid air passed over dry soil can stimulate volatilisation from urea. Further, leaf surfaces have only limited cation exchange capacity, low buffering capacity and posses considerable urease activity (Haynes and Sherlock, 1986). Losses of N from foliar urea through ammonia volatilisation are therefore likely.

The results from the series of experiments reported here then, in agreement with the findings of Poulton *et al.* (1990), indicate that gaseous losses, most likely by volatilisation, can be important for high rates of N applied as foliar urea. However, there is a clear indication that this effect is related to conditions following application. Applied under conditions likely to inhibit ammonia volatilisation, nitrogen recovery in the crop-soil system for N applied as foliar urea can be similar to that for N applied conventionally to the soil as solid ammonium nitrate or urea.

Soil mineral N in the autumn is usually taken to represent the quantity of N potentially at risk to leaching during the subsequent winter. Differences in soil <u>mineral</u> N in the autumn and nitrate leaching over winter, however, are unlikely to be related to differences in fertiliser N remaining in the soil at harvest; MacDonald *et al.* (1989) reviewing data from a number of winter wheat experiments, have shown that of the fertiliser N applied in the spring, only 1-2% is present in mineral forms in the soil at harvest. Differences in autumn soil mineral N and nitrate leaching are more likely to reflect differences in the mineralisation / immobilisation balance of <u>native</u> soil mineral N. Differences in the C/N ratio of incorporated plant residues are likely to be important in this respect. The decrease in apparent N recovery for the all foliar urea treatment in 1992, associated with the inferred gaseous N losses due to application of foliar urea sprays under conditions conducive to gaseous losses, was reflected in a significant increase in the C/N ratio of the incorporated straw + chaff. Due to the very short time interval between incorporation and soil sampling, the implication of the high C/N ratio of the incorporated straw + chaff favouring immobilisation of soil mineral N in the autumn for this treatment is somewhat tenuous, though the C/N ratio of straw + chaff from this treatment was double that for other treatments. The likely influence of this effect on over winter nitrate leaching, however, is more certain. Continued "mopping up" of native soil mineral N by immobilisation in the organic fraction, after soil sampling in the autumn, would have been favoured by the mild autumn weather and differences in nitrate leaching between treatments were noticeably larger than differences in autumn soil mineral N. In other years, where foliar urea was applied under conditions less conducive to gaseous losses, differences in the C/N ratio of incorporated straw + chaff were smaller, and no significant effect on nitrate leaching was recorded. The potential for reduced nitrate leaching in the short term by incorporation of cereal straw has been reported by others (Powlson *et al.*, 1985; Bertilsson, 1988; Jarvis *et al.*, 1989; Goss, 1990; Catt *et al.*, 1992).

The implication is clear, application of foliar urea under conditions conducive to gaseous losses, can potentially reduce nitrate leaching in the short term by affecting the C/N ratio of plant residues returned to the soil after harvest, and thereby influencing the mineralisation / immobilisation balance of native soil N in the autumn and early winter. The potential effects on nitrate leaching in the longer term, however, need to be considered; Powlson *et al.* (1987b) have reported that increased organic N due to immobilisation, leads to an increase in the basal rate of soil mineralisation (and therefore potentially leachable N) in the longer term. Evidence of this has been noted by Catt *et al.* (1992) in the Brimstone Experiment.

World wide there is considerable political and legislative pressure to reduce nitrate leaching. The World Health Organisation (WHO, 1996) set a guideline limit of 50 mg/l for the concentration of nitrate in drinking water. The maximum permissable concentration of nitrate in drinking water in the EU is 50 mg/l (Council of European Communities, 1980 and 1991), and in the USA 45 mg/l (United States Government, 1995). There is considerable controversy as to the justification of these limits with respect to the effects of nitrate on human health and the eutrophication of surface waters (Addiscott *et al.*, 1991). Gaseous losses of N are also an environmental issue. Gaseous losses as nitrous oxide, due to denitrification, contribute to global warming and cause depletion of the ozone layer (Addiscott *et al.*, 1991). N lost as ammonia by volatilisation is largely oxidised in the atmosphere to NO_3^- and returns to the land as HNO_3 in rainfall - so called "acid rain". Acid rain increases N inputs to forests and heathlands and can alter the composition of the vegetation, it also increases soil acidification and nitrous oxide emission and alters the nutrient balance of the ecosystem (Holtan-Hartwig and Bockman, 1994). The results of this work, indicate that N losses by nitrate leaching can be reduced at the expense of increased gaseous losses by denitrification and / or volatilisation. To attempt to weigh which of these forms of loss is of greater consequence is beyond the scope of this thesis. Both pathways represent a waste of valuable resources, to trade one for the other is futile. The key to reducing N losses from the plant-soil system, is through increased efficiency of fertiliser N use by the crop. There was an indication from the data of an increase in physiological N use efficiency by the crop for N supplied as foliar urea, similar yields were produced from lower apparent recovery of fertiliser N by the crop. Exploiting this property of foliar urea, together with some means of controlling gaseous losses, is likely to have significant benefits in terms of reducing N losses from the plant-soil system. The results from this study indicate that the simple measure of applying foliar urea sprays in the late evening rather than during the day can reduce gaseous losses.

Mean nitrate concentrations in the drainage water over winter below the EU limit of 50 mg/l were not recorded for any of the N treatments in any of the three years of the main experiment, and concentrations were commonly 1.5 to 3 times this limit. The high levels of nitrate leaching recorded are of particular concern given the cropping history and previous N applications at the site: the site has been in continuous cereals for some ten years, receiving no organic manures, and fertiliser N applications only marginally in excess of recommendations. Recently, Johnson *et al.* (1996) have reported nitrate concentrations of a similar order in the water draining from winter barley plots following winter wheat in an arable rotation receiving N fertiliser according to recommendations. Against this, the proposed action programme for Nitrate Vulnerable Zones to meet the EC Nitrate Directive (MAFF 1995b), seems somewhat insubstantial. The implication is clear, the current EU limit for nitrate in drinking water is unlikely to be met without further substantial changes in agronomic practice such as restricted N use, and / or the use of other measures such as water blending and nitrate stripping.

Davies and Sylvester-Bradley (1995) have recently predicted a decrease in nitrate leaching of about 7 kg N/ha per 100 kg/ha of fertiliser N withdrawn. This would represent a decrease in the mean nitrate concentration in the drainage water of between 9 to 21 mg/l, corresponding to a drainage volume of 150 to 350 mm respectively. Given the leaching concentrations recorded here, the potential impact of even such a severe restriction in fertiliser N use appears limited. Further, the financial penalties would be large. Sylvester-Bradley and Chambers (1992), showed that while a reduction of 20 kg N/ha applied to winter wheat would only result in a small average loss of £2/ha, a reduction of 80 kg N/ha, due to the shape of the N response curve, would result in an average loss of £23 to 40/ha.

In conclusion, with respect to N losses, the results of this study indicate that gaseous losses, most likely by volatilisation, can be important for high rates of N applied as foliar urea under certain conditions. Applied under conditions likely to inhibit gaseous losses, however, nitrogen recovery in the crop-soil system can be similar to that for N applied conventionally to the soil as solid ammonium nitrate or urea. Losses of N as nitrate in the drainage water from all treatments were high and mean nitrate concentrations were considerably in excess of the EU limit for all N treatments in each of the three years. The high levels of nitrate leaching are of particular concern given that the site has been in continuous cereals for some ten years, has received no manure, and N applications have been only marginally in excess of recommendations. Application of foliar urea under conditions conducive to gaseous losses, may potentially reduce nitrate leaching in the short term, by increasing the C/N ratio of the incorporated plant residues, thereby influencing the mineralisation / immobilisation balance of soil mineral N in the autumn and early winter. Exploiting the increased physiological N use efficiency indicated for N applied as foliar urea and controlling gaseous losses, is likely to have significant benefits with respect to reducing N losses from the plant-soil system. The potential effects on nitrate leaching in the longer term due to remineralisation of immobilised N, however, need to be considered.

8.3 Suggestions for Further Work

The results of this study have indicated the potential of foliar applied N to reduce nitrate leaching losses, due to increased C/N ratio of incorporated plant residues, associated with inferred gaseous losses, influencing the mineralisation / immobilisation balance of soil mineral N. Similar yields and lower apparent recovery of fertiliser N for N applied as foliar urea, indicate an increase in physiological efficiency of N use for foliar applied N taken up by the plant. Further scope to reduce nitrate leaching must lie in exploiting this increase in physiological efficiency, and at the same time controlling gaseous losses, thereby allowing N application rates to be reduced. Interception by the foliage around the time of the main N application in the spring as indicated in this study, is relatively low. The application of novel spray techniques and the use of adjuvants to increase foliar interception, together with the use of inhibitors to reduce gaseous N losses, are therefore likely to be important in exploiting the physiological efficiency of foliar N and reducing gaseous losses. Further work is required in this respect.

The potential of foliar urea to reduce nitrate leaching in the short term as discussed, may have implications for nitrate leaching in the longer term, due to remineralisation of N from organic matter. A clearer understanding of the likelihood and time-course of this effect is required.

In the study reported here foliar urea was applied as successive sprays every 4 to 5 days to reduce the risk of leaf scorch. In terms of the practical application of foliar urea to the farm situation, this is likely to present problems: the "spray window" i.e. the time available when weather conditions are suitable for spraying, is often limited around the time of the main N application. Further, four or five applications of foliar urea around GS 32, compared to one or at the most two for N applied conventionally to the soil as solid ammonium nitrate or urea, is unlikely to be economically justified. Further work regarding the suitability of tank mixing foliar urea with crop protection chemicals applied around GS 32 to 39, is therefore required to facilitate the practical application of foliar urea to the farm situation.

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Appendix

Work Published from the Thesis to Date

Readman, R.J., Kettlewell, P.S. and Beckwith, C.P. (1993). Foliar application of urea to winter wheat and nitrate leaching. In Cook, H.F. & Lee, H.C. (Eds.) *Soil Management in Sustainable Agriculture*. Wye College Press, Ashford, pp. 569-573.

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