Cattle slurry on grassland – application methods and nitrogen use efficiency

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Stanley T. J. Lalor

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Dedicated to the memory of my father,
Richard Samuel Lalor,

with whom my education in agriculture began.

Abstract

Lalor S.T.J., 2012. Cattle slurry on grassland – application methods and nitrogen use efficiency. PhD Thesis, Wageningen University, Wageningen, The Netherlands. With references – with summaries in English and Dutch, 183 pp.

Cattle slurry represents a significant resource on grassland-based farming systems. The objective of this thesis was to investigate and devise cattle slurry application methods and strategies that can be implemented on grassland farms to improve the efficiency with which nitrogen (N) in cattle slurry is recycled. The research focused on slurry application method and timing techniques that have been shown to reduce ammonia emissions following slurry application. Further, it was investigated whether the reduction in ammonia emissions translates into an increase in the N fertiliser replacement value (NFRV) of applied slurry. The study also included an economic analysis of the costs and benefits of low-emission slurry application methods, including a sensitivity analysis of the impact of costs that are likely to vary between farms.

A modelling study showed that low-emission application methods, which reduce herbage contamination and therefore permit slurry application into taller grass swards, increase the opportunity for application in spring when the slurry NFRV is relatively high due to the prevailing weather conditions that reduce ammonia volatilisation. The extent to which the opportunity for application in spring can be extended is affected by soil type, with more opportunity being afforded on more freely drained soil types. The extent to which herbage contamination is reduced by the low-emission application method was also affected by the grass height at application. Application methods that permit damage free traffic into taller swards permit greater potential to extend the opportunity for spring application.

In multi-year and multi-site field experiments, the NFRV of cattle slurry applied to grassland was increased by application using trailing shoe in short grass swards compared with conventional broadcast application using splash-plate. The NFRV was also higher when slurry was applied in April compared with June. However, there was no advantage over splash-plate in using the trailing shoe application method in taller grass swards, as the damage to the sward by the machinery traffic negated the benefits of reduced ammonia volatilisation.

An economic assessment showed that there was a net cost associated with adopting low-emission application methods on farms. The benefit of mineral N fertiliser savings due to ammonia emission abatement was not sufficient to offset the additional costs of adoption. The sensitivity analysis showed that the factors that had greatest impact on the costs were the assumed ammonia emission

abatement potentials, the volume of slurry being applied annually with each machine, and the hourly work rate of the equipment. The capital costs of increased tractor power contributed significantly to the total capital costs of adoption of low-emission equipment.

The results of this work were combined with literature data to devise updated NFRVs for slurry application to grassland in Ireland. The new advice includes differentiation of NFRVs based on application method, timing and residual N release. This represents a major step forward in advice to farmers for slurry application, and farmers have responded through improved management of application timing. The study shows that the combination of more application in spring and adopting low-emission application methods have a role to play in improving N efficiency from slurry in the future.

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Parts of this thesis have been published as peer-reviewed scientific articles. Chapter 2 was published by *Grass and Forage Science, 63 (2008), 531-544*. Chapter 3 was published by *Journal of Environmental Quality 40 (2011), 362–373*. Chapter 4 has been published by *Grass and Forage Science, (2013) (doi: 10.1111/gfs.12051)*. Chapter 5 has been accepted for publication as a Book Chapter in *Costs of ammonia abatement and the climate co-benefits (Reis, S., Sutton, M.A., Howard C. (Eds.))*. Chapter 6 was presented as an invited paper at the meeting of the International Fertiliser Society in Cambridge, UK, on 6th December 2012 (Proc. No. 712, 2012).

For this thesis, the text of the published articles or the submitted manuscript has been integrally adopted. Editorial changes were made for reasons of uniformity of presentation in this thesis. Reference should be made to the original article(s).

1

General Introduction

S.T.J. Lalor

1.1. Introduction

The application of manure to land is a common feature of agricultural systems, particularly in livestock and mixed farming systems where manure is often applied to land on the farm where the manure is produced. Manure is a valuable source of nutrients that can be recycled by crops following application, and hence reduce mineral fertiliser requirements and costs. The quantity of manure available for application, and hence the quantity of nutrients it contains, depends on the type, diet and management of animals producing the manure and the type and management of animal housing and manure storage facilities (O'Bric, 1991).

The efficiency with which nutrients are recovered from manure following application to land tends to be relatively low, and also highly variable (Schröder, 2005b). As a result, mineral fertilisers have been viewed as a more dependable source of nutrients for crops, as the total nutrient concentration is more reliable, and the recovery of these nutrients by crops is perceived to be higher and more efficient than with manures. Consequently, manures have tended to be applied to land in ways that under-utilised their full potential as a nutrient source (Smith and Chambers, 1995). This has contributed to environmental issues associated with farm-level and soil-level surpluses of nutrients such as nitrogen (N) and phosphorus (P) and gaseous emissions of ammonia (NH_3) (Oenema *et al.*, 2007).

1.2. Slurry production in grazing systems

Manure produced by housed animals can be collected and stored as either liquid or solid manure. Liquid manure is often referred to as slurry, defined as a mixture of faeces and urine, usually mixed with some bedding material and water, produced by housed livestock and with an indicative dry matter concentration below 10% (Pain and Menzi, 2011). Slurry is commonly produced in both cattle and pig production systems where minimal or no bedding material is used and where faeces and urine are collected in tanks under slatted flooring or are scraped off solid floor surfaces and stored in tanks either within or outside the animal housing.

Manure is also produced and deposited directly on land in systems that involve grazing grass *in situ*. While manure deposited in this way will also be a source of nutrients for plants, the inability to either spatially and temporally manage the distribution of this manure means that the efficiency of recovery of these nutrients by plants tends to be low, and often has little impact on application rates of complementary fertiliser nutrients (especially N) to grassland. Therefore, the longer time periods that animals spend grazing and depositing manure directly to land, the lower the opportunity to optimise the utilisation of the overall manure produced annually.

Slurry is commonly cited in advisory literature for its N, P and potassium (K) fertiliser replacement value (FRV) (Coulter and Lalor, 2008). Some advisory sources also highlight the potential contribution of slurry to sulphur (S) and magnesium (Mg) nutrition in crops (DEFRA, 2010). Slurry is usually highly variable with regard to the total nutrient concentration, with up to ten-fold variation being observed (O'Bric, 1991). The variability of slurry in terms of total nutrient concentration and the subsequent immediate and long-term plant availability of the nutrients applied represents a significant barrier to farmers being confident of the full FRV potential of manures.

Manures play a key role in recycling nutrients within grazing systems that include a housing period, particularly on farms where the majority of the feed used during the housing period is produced on the farm. In this case, it is typical that manure is applied to the areas from which the winter feed is harvested. In most cases, this winter feed will be grass silage or maize silage. However, the same principle also applies to systems where the diet consists of a high proportion of cereals or other concentrate feeds. By returning the manure to the areas where the feed was harvested in this manner, it effectively closes a loop in the nutrient cycle, as the nutrients that the manure contains will have originated from the soil in the area from where the feed was harvested (Figure 1.1).

This simplified model (Figure 1.1) also includes inputs of nutrients in fertilisers and imported feeds, and removals of nutrients from the cycle in animal products and environmental loss pathways. The overall efficiency of the nutrient cycle at a farm gate level can be low in the case of N in grassland systems, with transfer efficiencies of 10-40% being typical in dairy systems (Schröder, 2005b). Recycling manure nutrients can contribute to the combined objectives of a) replacing and supplying nutrients to areas used to grow crops for conservation as winter feed; and b) reducing the environmental impacts of nutrient application caused by excessive manure application and subsequent nutrient surpluses on other lands. In grazing livestock and mixed farming systems, this strategy can be achieved with relative ease. However, in more intensive livestock enterprises, the dislocation of livestock production from the land where their feed is produced makes this strategy more challenging, mainly due to logistical reasons and transport costs associated with manure movement over longer distances (Lalor and Hoekstra, 2006).

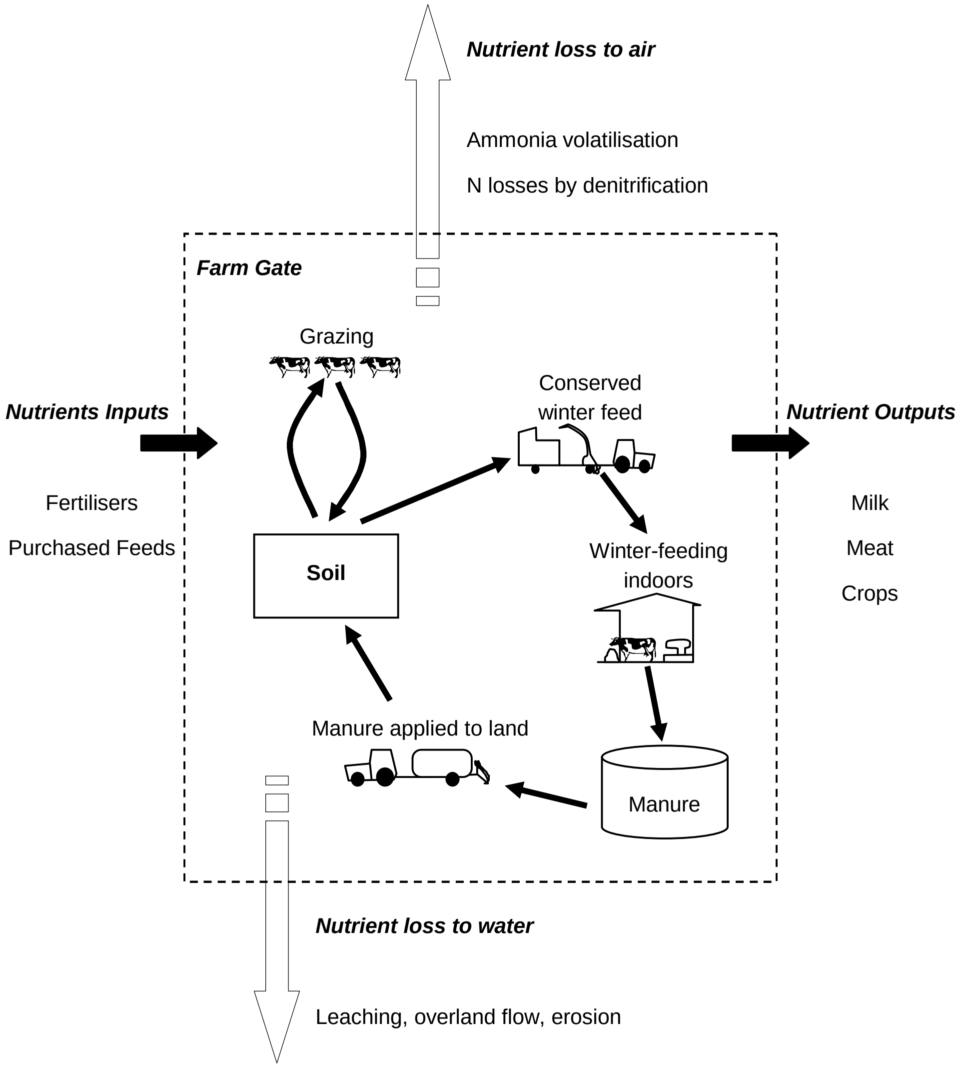

Figure 1.1. Nutrient cycling in farm systems where nutrients in manures are returned to the areas from which the feeds are harvested.

1.3. Slurry N efficiency

Nitrogen is commonly the nutrient that most limits net primary production in terrestrial ecosystems (Vitousek and Howarth, 1991). It is therefore the nutrient that is often applied at highest rates in grassland and crop systems (Lalor *et al.*, 2010). In slurry, it is commonly considered to be the most variable nutrient in terms of recovery and FRV. Precise application of N via fertilisers and manures to meet crop demand requires quantitative insight in N cycling processes and losses. Nitrogen in soil is subject to transformation processes that can temporarily immobilise or mineralise N. Ammonia volatilisation, nitrification, leaching, denitrification and related processes can also result in N in soils being lost, depending on environmental conditions (Figure 1.2). Hence, the timing of fertiliser and manure applications to supply plant available N close to periods when plants have high uptake is critical.

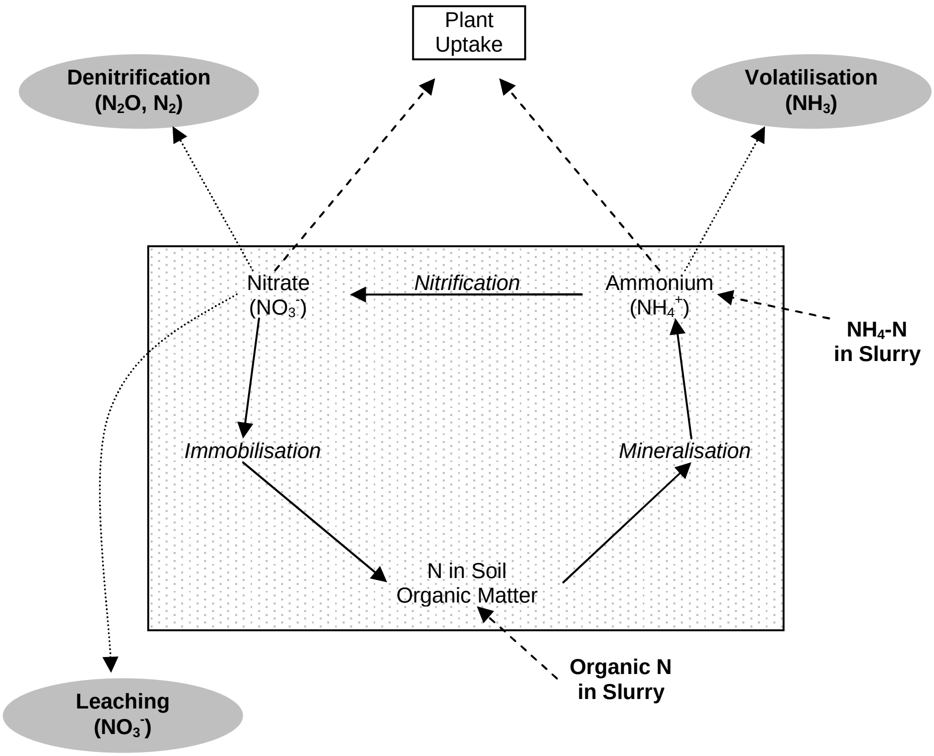

Figure 1.2. Principle pathways and processes of N cycling in the soil, including gaseous and leaching N loss pathways and N inputs from applied slurry. (Possible losses via overland flow and erosion are not shown here).

Nitrogen in slurry can be loosely categorised into two main components. Approximately 40-60% of the total N in cattle slurry is in an organic form, derived principally from the faecal matter in the slurry (Beegle *et al.*, 2008). This fraction of the total N is not immediately available for plant uptake (Schröder, 2005b), but can become available to plants over time as mineralisation and nitrification convert organic N in soil into plant available ammonium (NH_4^+) and nitrate (NO_3^-). The recovery of this component of the slurry N is considered to be low, and is often not taken into account in fertiliser recommendations. However, the recovery of this organic fraction has been shown to contribute to N supply in the year of application and in subsequent years (Schröder, 2005b; Schröder *et al.*, 2005; Bosshard *et al.*, 2009). In a study using ^{15}N labelled slurry N fractions, Hoekstra *et al*. (2011) reported recovery rates in herbage of organic N derived from faeces in slurry of 9% in the 6 week period after application, and a further 7% in the residual harvests up to 63 weeks after application. The cumulative recovery of 16% of the organic N over the 63 week period in this study corresponds to results of other multiyear experiments that concluded that the recovery of the organic N in slurry in the first year after application was between 20 and 33% (Schröder *et al.*, 2005; Schröder *et al.*, 2007).

The remaining 40-60% of the total N in slurry is present in the form of NH_4^+, which is mainly derived from urea excreted in urine, and is immediately available for plant uptake (Beegle *et al.*, 2008). However, the recovery and FRV of this NH_4-N in slurry can be highly variable, and is often low, as a result of the potential for ammonia (NH_3) losses to the air due to a process called volatilisation. Other gaseous N losses (N_2O, NO and N_2) also occur due to denitrification.

1.3.1. Ammonia volatilisation

Ammonia volatilisation occurs when NH_4^+ in the aqueous phase in slurry is lost to the air as NH_3 gas. The process occurs by way of a number of equilibrium reactions that are ongoing within the slurry and at the interface between the slurry and the air following application. These reactions are summarised by Huijsmans (2003) and represented in Figure 1.3. Ammonium present in the aqueous phase in slurry is in equilibrium with NH_3 in slurry in the aqueous phase. The reaction involves the association or dissociation of a H^+ ion, and is therefore dependant on slurry pH and temperature. Decreasing the slurry pH will decrease the conversion of NH_4^+ to NH_3. The conversion of NH_3 in the aqueous phase into the gaseous NH_3 in the slurry, and the exchange of gaseous NH_3 between slurry and air, depends on the concentration gradients between these phases of the NH_4^+ and NH_3 pools, and the removal of gaseous NH_3 in air via diffusion and wind.

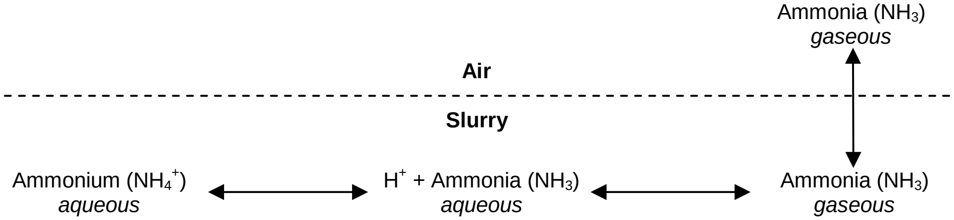

Figure 1.3. Process of NH_3 volatilisation from slurry to air.

The recovery of NH_4-N from slurry by crops will be low where NH_3 volatilisation following application is high. Therefore, one of the key objectives for slurry application practices should be to minimise the volatilisation of NH_3. Huijsmans (2003) identified the following factors that contribute to NH_3 volatilisation:

1) dry matter (DM), NH_4-N concentration and pH of slurry;
2) meteorological conditions, principally temperature, wind speed, rainfall and relative humidity, at and around the time of slurry application;
3) soil properties (moisture content, pH, cation exchange capacity and infiltration capacity) and crop characteristics such as canopy height; and
4) slurry placement (application technique).

These factors also interact with each other so the relative impact of each factor will depend also on other prevailing conditions and circumstances regarding the soil, crop and slurry involved.

There can be a wide range in the extent to which the total ammoniacal N (TAN) applied in slurry is volatilised. In a study in the UK, Smith *et al.* (2000) measured ammonia volatilisation following broadcast application of dairy and beef slurries to grassland in the range of 22 to 96 % of TAN applied. In experiments in the Netherlands, Huijsmans *et al.* (2001) measured a range in emissions following broadcast application to grassland of 27 to 98% of TAN in slurry applied. The EMEP/EAA guidebook (EEA, 2009) is designed to facilitate reporting of emission inventories by countries to the UNECE Convention on Long-range Transboundary Air Pollution and the EU National Emission Ceilings Directive. This Guidebook indicates an average ammonia emission factor (EF) by volatilisation of 55 % of the TAN from cattle slurry when applied with splash-plate. However, a recent review of ammonia emission data by Sintermann *et al.* (2012) questioned this average EF for broadcast application.

1.3.2. Improving N efficiency by reducing volatilisation

The factors that affect volatilisation are not all fully under the control of a farmer at the time of application. Characteristics of slurry such as pH and NH_4-N content are principally a function of the animals producing the slurry and their diet (O'Bric, 1991). The slurry DM concentration can be decreased by adding water to slurry in storage. This will reduce the potential for NH_3 emissions after application. However, this also has the effect of increasing both storage capacity requirements and the volume of slurry to be applied. In many farmyards, the effect of water addition to slurry in storage on the DM concentration is a function of the fixed farmyard infrastructure as much as subsequent management. For example, rainfall on outdoor and unroofed slurry stores or unroofed soiled areas, or water used for washing milking facilities, can act as a source of water for dilution of slurry in certain circumstances.

Of more immediate control to farmers are the factors of 1) application timing; 2) application method; and 3) the presence or condition of the crop canopy at the time of application. The influence of meteorological factors on ammonia volatilisation has been shown to allow for associations to be made between temporal variation in application timing and ammonia volatilisation following land application of manures (Moal *et al.*, 1995; Sommer and Olesen, 2000; Reidy and Menzi, 2007). A distinction is commonly made in advisory information between application in spring and summer. In spring, conditions are cooler and more humid, which result in a higher NFRV compared to application in warmer and drier conditions more typical of summer (Coulter, 2004; DEFRA, 2010).

The broadcast (splash-plate) application method is a common slurry application method in most regions, including Ireland. However, it has been well established that application using splash-plate can be accompanied by high N-losses through ammonia volatilisation (Malgeryd, 1998; Mattila, 1998; Morken and Sakshaug, 1998; Smith *et al.*, 2000; Misselbrook *et al.*, 2002). In these comparative studies, N-emissions were progressively reduced by using low-emission spreading techniques such as band spreading, trailing shoe and injection. The literature remains inconclusive about the magnitude of such reductions, since N-utilisation and N-losses depend on interactions between grass cover and crop growth rates (Misselbrook *et al.*, 2002).

Reducing NH_3 volatilisation in itself does not automatically infer improved N utilisation by herbage. It only results in more N from slurry being retained in the soil in a form (NH_4^+) that is immediately available to the grass crop. The efficiency with which the N not volatilised will be taken up by plants and assimilated into harvestable herbage mass is also important in determining the relationship between volatilisation and FRV. Hoekstra *et al*. (2010a) measured the recoveries in the soil at the end of the growing season of the year of application ranging from 20 to 36% of NH_4^+-N applied in slurry. The majority of this N was found in the organic N pool in the soil. This indicates the potential for NH_4^+ not volatilised to be immobilised and retained by the soil rather than taken up by plants. The efficiency of utilisation of N that is taken up by plants is also a factor to consider. Schils and Kok (2003) compared slurry application methods and found that shallow injection increased the apparent N recovery of slurry by 57% compared to splash-plate. However, the effect was smaller when the methods were compared on the basis of dry matter yields; shallow injection increased the efficiency by 45%. This demonstrates that increased N uptake in herbage may not always correspond to increased grass yields, as the effect may be seen as an increase in N concentration in herbage rather than as N assimilated into herbage mass. Therefore, the measurement of N efficiency based on N uptake or dry matter effects can impact on how slurry application strategies should be compared.

1.4. Current practice with slurry management in Ireland

Bovine farming systems in Ireland are dominated by pasture-based dairy and beef production, and typically include a winter housing period ranging in length from approximately two to six months in duration, depending on the system, location and soil type. Approximately 80% of the manure collected during the winter housing period is managed as slurry. Farmyard manure produced in straw bedded housing systems is also common, but accounts for only approximately 20% of the total manure produced (Hyde and Carton, 2005). Approximately 20 Mt of slurry were estimated to be produced in Ireland in 2009 from the 6.2 million bovine animals in the country (Hennessy *et al.*, 2011a). By comparison with bovine systems, only relatively small volumes of other animal manures (approximately 2.5 Mt of pig manure and 0.17 Mt of poultry manure) are produced in Ireland (FSAI, 2008).

Cattle slurry in Ireland has traditionally been applied to grassland after silage harvest in summer months. In 2003, it was estimated that 34%, 52%, 16% and 6% of slurry was applied in spring, summer, autumn and winter, respectively (Hyde et al., 2006). Summer application after silage harvest offers simplicity as a management strategy as it usually coincides with a period when: a) soil conditions are dry to permit traffic with slurry application equipment, and b) contamination of a grass canopy with slurry that will affect subsequent grazing preference or silage quality is minimised as the sward is bare following cutting for silage. The issue of sward contamination is particularly relevant given that the splash-plate system of slurry application has been the dominant slurry application method in Ireland to date (Hyde and Carton, 2005).

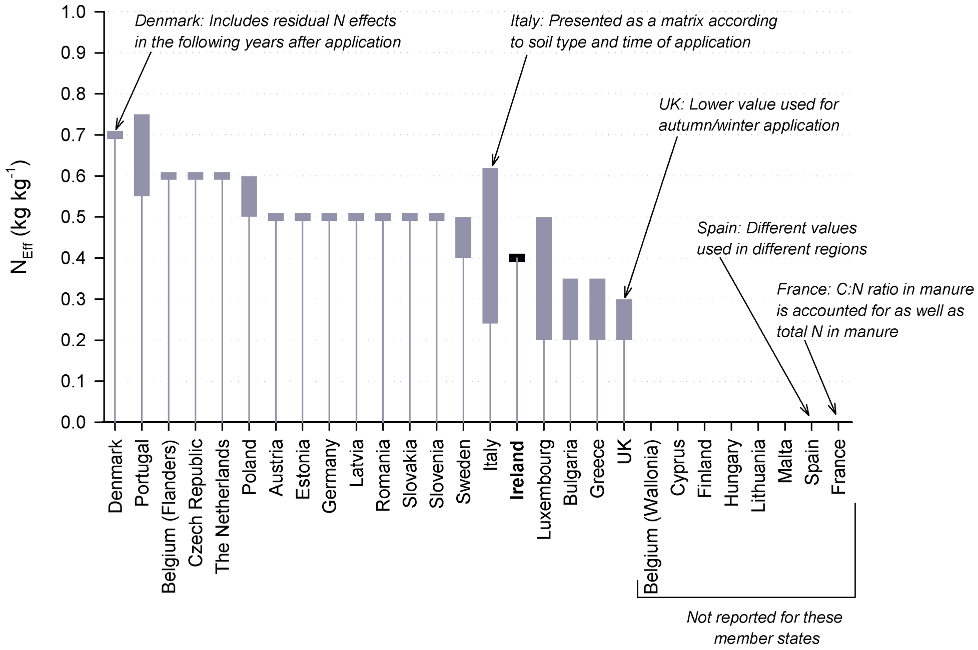

Figure 1.4. Reported mean values (and range where applicable) of manure-N efficiency (N_{eff}) from cattle slurry (kg kg^{-1} of total N) in the season after manure application in Nitrates Action programmes in EU member states (MS) (adapted from Webb et al., 2010b). (The value used for Ireland is shown in black).

The tendency towards application in summer has been contrary to existing advice on slurry NFRV in Ireland (Coulter, 2004) which indicates that the NFRV is higher when the slurry is applied in the spring period (February, March and April) compared to summer (May, June, July). However, the advice only differentiates NFRV based on timing and takes no account of potential benefits of changing application method. The current advice also suggests that the maximum NFRV achievable is 0.25 kg kg^{-1} with spring application. However, this upper limit is considerably lower than those assumed in advice in other countries, and in the EU Nitrates Directive Action Programme in Ireland. Webb *et al*. (2010b) summarised manure-N efficiency values in Nitrates Action Programmes across EU member states (Figure 1.4). While manure-N efficiency is not clearly defined or fully comparable between Action Programmes, it is considered in this case to be the proportion of the manure-N available to crops in the season after manure application. In the case of Ireland, two conclusions emerge from these data: 1) the target of 0.40 kg kg^{-1} is substantially higher than the NFRV currently assumed in agronomic advice; and 2) the target of 0.40 kg kg^{-1} set in Ireland's Action Programme is lower than those set in many other member states, with values ≥0.60 kg kg^{-1} being assumed in a number of other Action Programmes. Therefore, there appears to be scope for improvement of the NFRV of applied cattle slurry in Ireland, both in the advice given to farmers, and in what farmers can achieve in practice.

1.5. Slurry application strategies – timing and method

The timing and method of application are two key parameters that influence ammonia volatilisation and subsequent NFRV. The low level of usage of low-emission application methods such as trailing hose, trailing shoe and shallow injection in Ireland suggests that there is potential to improve the NFRV that can be achieved on farms. The review of Webb *et al*. (2010a) included a summary of NH_3 emission abatement efficiencies for the low-emission application methods of trailing hose, trailing shoe and shallow injection used in grassland (Table 1.1). Similar values of 30% (trailing hose), 60% (trailing shoe), and 70% (shallow injection) are given in the UNECE guidance document on ammonia emission abatement (UNECE, 2007).

Table 1.1. Summary of results of experiments to measure the abatement efficiency of low-emission slurry methods, % reduction in NH_3 emissions compared with broadcast application using splash-plate (Webb et al., 2010a).

Application method	No. of papers reviewed	Mean % Reduction	Range (%)
Trailing hose	5	35	0-74
Trailing shoe	2	64	57-70
Shallow injection	5	80	60-99

The trailing shoe is the low-emission application method that is most likely to be of wide scale applicability in Irish grassland systems. One reason for this is that the trailing shoe is likely to maximise the reduction in herbage contamination compared to trailing hose. The slurry is applied with trailing shoe directly to the soil at the base of the sward canopy due to the presence of the solid ‘shoe-’ or ‘foot-’ like coulters at the base of the outlet pipes. By comparison, the slurry application is less targeted to avoid contamination of herbage using trailing hose. Compared to shallow injection, the trailing shoe also reduces the draught power requirement and difficulties associated with stony and/or variable soil type (which are common to Irish grasslands (Gardiner and Radford, 1980)). Therefore, the trailing shoe is likely to be a more widely applicable method across the broad and variable range of Irish grassland soils.

Of the low-emission spreading techniques, the trailing shoe has also been found advantageous under UK conditions, for the following reasons:

1) It places slurry underneath a closed grass canopy, thus facilitating application to growing swards. This allows application to take place when grass growth rates and hence nutrient demand are higher.

2) In addition, placement of slurry underneath the canopy restricts surface interactions between slurry and air (reduced wind and radiation), thus reducing N-loss through volatilisation (Malgeryd, 1998; Mattila, 1998; Morken and Sakshaug, 1998; Smith *et al.*, 2000; Misselbrook *et al.*, 2002).

3) It reduces contamination of silage with slurry and subsequent risks of poor silage quality (Laws *et al.*, 2002).

4) In grazed swards, it reduces herbage rejection by grazing bovines (Laws and Pain, 2002).

It remains to be firmly established whether application strategies that reduce NH_3 volatilisation will increase the utilisation of slurry N by the grass to reduce mineral N fertiliser requirements. Some studies have reported that the utilisation of slurry N is increased with shallow (open-slot) injection and with surface banding techniques compared with splash-plate application (Schils and Kok, 2003; Bittman *et al.*, 2005; Schröder *et al.*, 2007; Bhandral *et al.*, 2009), while results of increased N utilisation by the crop have been inconsistent in other experiments (Smith *et al.*, 2000; Laws *et al.*, 2002; Bittman *et al.*, 2005). Results from Northern Ireland suggest that trailing shoe applications may increase herbage mass by 21% compared with splash-plate applications (Binnie and Frost, 2003). However, this increased utilisation had been dependent on grass cover, timing of application, and on the physical environment, that is, soil and weather conditions (Smith *et al.*, 2000; Misselbrook *et al.*, 2002). As a result, the NFRV of slurry applications has been difficult to predict. Anecdotal evidence suggests that this unpredictability is encouraging farmers to discount the NFRV of slurry in the fertilisation of grasslands. Therefore, both the establishment of agronomic responses, and the predictability of these responses warrant further research.

The relatively low rate of adoption of slurry application in spring of 34% (Hyde *et al.*, 2006), despite the differentiation made between higher NFRV with spring application in agronomic advice (Coulter, 2004) also suggests that there is potential to apply more slurry in spring by overcoming barriers such as soil trafficability and herbage contamination, and improving the confidence and reliability with which a farmer can depend on slurry N as a viable replacement for mineral N fertiliser.

1.6. Objective and approach of the research

The overall objective of the body of research detailed in this thesis was to increase the quantitative understanding of the utilisation of N from cattle slurries applied to grassland as function of application method and timing. More specifically, the objective was to investigate and devise cattle slurry application methods and strategies that can be implemented on grassland farms to improve the efficiency with which N in cattle slurry is recycled. My research was conducted to address gaps in the knowledge regarding how the benefits of reducing ammonia emissions following slurry application translate into benefits in NFRV of applied slurry and fertiliser advice to farmers. I also quantified how the benefits of reduced sward contamination with low-emission application methods could impact on the flexibility and opportunity for slurry application in the spring period. An economic assessment of the net cost of adopting low-emission application methods was also an objective of the study.

My research focused on slurry application method and timing techniques that have been shown to reduce ammonia emissions following slurry application. I have investigated whether the reduction in ammonia emissions, which is environmentally beneficial, actually translates into an increase in the NFRV of slurry applied to grassland. This information is seen as critical to transferring knowledge of slurry application technologies to farmers, since a significant increase in yields, and/or reduced fertiliser costs is required to encourage a change in practice.

The study also sets about evaluating the costs of slurry application methods and strategies, particularly in the context of where slurry application equipment infers additional cost on farmers. An economic analysis of the costs and benefits of low-emission slurry application methods was conducted, and included a sensitivity analysis of the impact of costs that are likely to vary between farms.

The final objective of this study was to collate the results of this and other research to devise a practical but effective strategy for slurry application management on grassland farms that considers environmental targets of improving water quality and reducing ammonia emissions with the practical and economic considerations of a farm system. This was done to improve the advice given to farmers in order to achieve an impact at farm level regarding improved slurry management practices and outcomes.

1.7. Outline of this thesis

This thesis is arranged in seven chapters. Chapter 1 (this chapter) provides a general introduction to the challenges presented and options available for slurry management in grassland systems to increase N efficiency and reduce NH_3 emissions and associated environmental impacts.

Chapters 2, 3, 4 and 5 describe individual investigations within the overall study. Chapter 2 describes a model developed to predict slurry spreading opportunities in the spring period of the year when slurry NFRV is normally highest due to prevailing climatic conditions. The model is used to estimate how opportunities for spreading are influenced by slurry application method, given that low-emission application methods are considered useful in overcoming difficulties of herbage contamination following slurry application. Chapters 3 and 4 describe the results of multi-site and multi-annual field experiments conducted to investigate the effects of slurry application method on NFRV. Chapter 3 describes the results of treatments comparing splash-plate and trailing shoe for NFRV from cattle slurry applied in April and June. Chapter 4 details comparisons made between treatments with slurry applied using the trailing shoe method at different timings and into different grass sward heights. Chapter 5 describes an economic cost/benefit analysis conducted to examine the marginal additional costs of low-emission slurry application method adoption compared with conventional splash-plate application. This analysis includes an estimation of the cost savings that can be achieved due to reduced fertiliser N inputs where NFRV is increased. A sensitivity analysis of the effect of changes in component costs on the total marginal cost is also included to permit a wider application of the results to other scenarios.

In Chapter 6, the results of the four individual study chapters, together with other work on slurry application both within Ireland and from elsewhere, are combined to provide some practical and effective guidelines and advice for slurry management in grassland, considering the various influencing factors of environment, agronomy, practicality and costs to devise advice recommendations for the future.

Chapter 7 provides a general discussion of the findings of the study in the context of existing and emerging research and legislation that impact on cattle slurry management on farms. Gaps in knowledge are also identified.

The thesis also includes an abstract of the overall study, and summaries in English and Dutch.

2

Low ammonia emission application methods can increase the opportunity for application of cattle slurry to grassland in spring in Ireland

S.T.J. Lalor and R.P.O. Schulte, 2008. Grass and Forage Science, 63, 531-544.

Abstract

Application of slurry in spring to grassland in northwest Europe increases the efficiency of nitrogen recovery compared with the application in summer. In Ireland, however, more than 50% of slurry is applied in the summer. The splash-plate method of application, most commonly used in Ireland, can make application in spring difficult because of the risk of contamination of grass with slurry, affecting subsequent silage quality and grazing preferences. This study evaluated the potential of low-emission spreading methods to increase the opportunity for spring application of slurry using an agro-meteorological modelling approach. Weather data from two weather stations were combined with data on grass growth from two nearby sites. Using three soil drainage classes (well, moderate and poor), each with a typical regime of grassland management, a database of soil moisture deficits, drainage, patterns of grazing and cover of grass herbage was developed for three hypothetical management systems, one for each soil drainage class, at each site. Simulations of four slurry application methods (splash-plate (SP), band-spreader (BS), trailing shoe (TS) and shallow injection (SI)), subject to a series of constraints, were compared over an eight year period (1998–2005) in order to determine the number of days during the period from 1 January to approximately 10 May of each year, when it was considered that grassland was suitable for application of slurry. These constraints were: (i) restrictions on spreading imposed by current legislation in Ireland; (ii) the period before occurrence of drainage or overland flow; (iii) soil trafficability; (iv) the time lag before a subsequent grazing or harvest event; and (v) herbage mass of the pasture. On well and moderately drained soils, the model predicted that the highest number of days available for slurry spreading was found for the TS method followed by the BS, SI and SP methods. There was no difference between application methods in the number of available days on poorly drained soils.

Keywords: cattle slurry, application methods, ammonia emissions, grassland, grass growth model

2.1. Introduction

Approximately 80% of the manure produced by cattle in Ireland is managed as slurry (Hyde and Carton, 2005). Legislation recently implemented in Ireland for compliance with the EU Nitrates Directive (91/676/EEC) (Anon, 1991) requires that from 2010, 40% of the nitrogen (N) contained in cattle slurry shall be deemed available for uptake by herbage in the year of slurry application (Anon, 2006). The availability of N in slurry is affected by a combination of factors including application rate, timing and method of application and composition of slurry (Schröder, 2005b). Other initiatives, such as the Gothenburg Protocol (UNECE, 1999) and the EU National Emissions Ceilings Directive (Anon, 2001), require reductions in gaseous emissions of ammonia which will also impact on how cattle slurry is spread on grassland in the future in Ireland. Hyde *et al.* (2003) estimated that spreading of cattle slurry on grassland is the source of approximately 30% of the annual ammonia emissions from Irish agriculture and concluded that an integrated approach, including the use of novel 'low-emission' spreading techniques, so called because of their potential to reduce the gaseous emissions of ammonia resulting from spreading slurry on grassland, represent the best means by which the targets for reducing ammonia emissions may be met.

Almost all the applications of cattle slurry to grassland in Ireland are performed using a splash-plate (SP) (broadcast) application method (Hyde and Carton, 2005). This is a relatively simple method and the equipment is inexpensive to purchase, maintain and operate. Low-emission application methods, such as the bandspreader (BS), trailing shoe (TS) and shallow injection (SI) methods, are available as alternatives to the SP method but are more expensive to purchase and maintain (Ryan, 2005). These methods have been shown to be of benefit in reducing ammonia emissions from the spreading of slurry on grassland (Malgeryd, 1998; Smith *et al.*, 2000; ALFAM, 2001; Misselbrook *et al.*, 2002), and in increasing the apparent recovery of slurry N in herbage (Schils and Kok, 2003; Schröder *et al.*, 2007). Low-emission methods apply slurry in lines, thereby reducing the proportion of the grassland that comes into contact with the slurry (Figure 2.1). Laws *et al.* (2002) showed that silage quality was adversely affected by slurry application using SI and SP methods, whereas slurry application using the TS method had no negative effect on silage quality even with an application 2 weeks before harvest. The TS and SI methods have also been shown to reduce the rejection of herbage by cattle caused by slurry application to grazed pasture compared with the SP method (Laws *et al.*, 1996; Laws and Pain, 2002). Low-emission application methods can offer advantages over the SP system, mainly by allowing the more flexible timing of slurry applications, particularly in spring as the requirement for dry soil conditions need not coincide with the relatively short period when herbage masses are low enough to allow slurry application with the SP method (Lalor and Schulte, 2007).

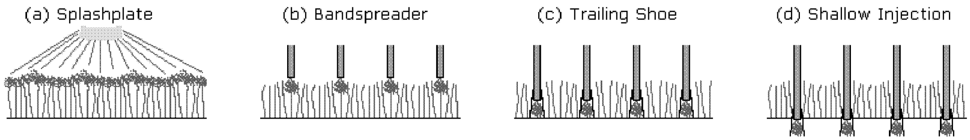

Figure 2.1. Diagrammatic representation showing slurry placement (a) on top of herbage and over entire spreading width with splash-plate method; (b) in lines on top of herbage with band-spreader method; (c) in lines below herbage, but above the soil surface, with the trailing shoe method; and (d) below the soil surface (approximately 5 cm) with the shallow-injection method.

Extending the period of slurry application also offers considerable potential for increasing the N fertiliser replacement value (FRV) of slurry. It is suggested that the NFRV of slurry applied with the SP method will be 0.25 kg kg^{-1} if applied in spring (March / April), and only 0.05 kg kg^{-1} if applied in summer (June / July) in Ireland (Coulter, 2004). In the UK it is suggested that values for spring application are 0.35 kg kg^{-1} and for summer application are 0.20 kg kg^{-1} (DEFRA, 2006). Pain *et al.* (1986) found a difference of 0.14 kg kg^{-1} in N efficiency of an application of 80 kg N ha^{-1} as slurry in March / April (0.38 kg kg^{-1}) compared with an application in May / June (0.24 kg kg^{-1}). It is estimated that only 0.34 % of cattle slurry in Ireland is applied in the spring, with the remainder being applied primarily in summer months when N utilisation is lower (Hyde and Carton, 2005). The current strategies for slurry management being adopted in Ireland will not help achieve the target NFRV of 0.40 kg kg^{-1} as set out in the new regulations.

Timing of slurry application is critical for maximizing N availability to herbage. Applications in autumn and winter can lead to high leaching losses, whereas summer applications are more prone to gaseous ammonia losses because of warmer and drier air and soil conditions (Smith and Chambers, 1993; Schröder, 2005b). Application in spring appears to be optimal as it allows nutrients to be applied at a period when uptake by herbage is high, and when ammonia and leaching losses are relatively low (Carton and Magette, 1999). While application in spring is desirable to maximise N use efficiency, soils are often too wet for slurry application. Schulte *et al.* (2006) showed that in a year of high rainfall, some parts of Ireland have only 25 days during which soils are dry enough for damage-free soil trafficking, with most of these occurring during the summer. Moreover, slurry application with the SP method results in the application of a thin layer of slurry to the entire spreading width of the machine. This can result in contamination of the pasture, and may subsequently affect silage quality and grazing preferences (Pain *et al.*, 1974). The current practice of applying slurry in summer after herbage has been harvested for silage can be partly explained as a means of reducing the risk of contamination of pastures. Application in spring using the SP method is confined to pastures with a low herbage mass for this reason, but often these conditions do not occur in spring when soil conditions permit damage-free soil trafficking. This results in applications being postponed until the next available instance of low herbage masses, normally after first-cut silage, when risks of ammonia loss are higher and the NFRV is lower. By reducing the risk of contamination, low-emission methods allow application in pastures with a higher herbage mass, thereby increasing the likelihood of more days when slurry can be spread in the spring when N demand by herbage is high, and risk of ammonia loss is relatively low.

The objective of the study was to evaluate the number of days in spring that slurry can be applied and to compare the commonly used SP method with alternative low-emission methods, namely BS, TS and SI, using an agro-meteorological modelling approach.

2.2. Model description

The factors that determine whether a grassland is suitable for spreading slurry are legislative restrictions (Anon, 2006), risks of nutrient losses to watercourses (Parkes *et al.*, 1997), soil trafficability (Schulte *et al.*, 2006) and the risk of contamination of herbage as determined by the time-lag before subsequent grazing or harvesting for silage and the herbage mass at the time of application (Laws *et al.*, 2002). In order to evaluate the potential of the different application methods to increase the number of days when slurry can be applied in the spring, each method was assessed for its ability to satisfy these criteria.

The model was designed, using Microsoft Excel, to determine the number of days during which 20% or more of the area of grassland of a hypothetical dairy system could be deemed suitable for spreading slurry with a specific application method. The value of 20% was chosen as the lower limit on the amount of grassland that would be required for the farmer to justify the preparation of the slurry (storage tank agitation) and the equipment to carry out the spreading operation.

The time step of the model was a day. The period of interest was from Julian day 1 to 130 (1 January to approximately 10 May). Four application systems, i.e. SP, BS, TS and SI, were compared for three soil types at two sites. The area of grassland of the hypothetical dairy system was divided into 100 units. The model classified each unit as either a grazing or silage area based on a grassland management regime specific to the soil type and location. The classification of each unit as being available or unavailable on each day was according to: (i) suitable soil trafficking conditions; (ii) herbage mass of the pasture; (iii) days before a subsequent grazing or harvesting event; and (iv) days without drainage or overland flow. The threshold values used in the model are shown in Table 2.1. Any day on which 20% or more of the area was available was counted in the output as 1 day suitable for spreading slurry. Figure 2.2 shows a diagrammatic representation of the model.

Table 2.1. Minimum threshold levels of each constraint used in the model to determine suitability for slurry application by four methods (SP, splash-plate; BS, band-spreader; TS, trailing shoe; and SI, shallow injection).

	Method			
	SP	BS	TS	SI
Risk of loss to water: minimum period post-spreading with no drainage or overland flow (days)	2	2	2	2
Soil trafficability: minimum soil moisture deficit (mm)	10	10	10	10
Minimum time lag before subsequent grazing or harvesting event (days)	42	42	42	42
Maximum herbage mass (kg ha^{-1} DM)	300	600	800	600

2.2.1. Legislative restrictions

Current legislation in Ireland for compliance with the Nitrates Directive (Anon, 2006) specifies periods within which slurry application is prohibited. For this purpose, Ireland is divided into three zones (see Figure 2.3). The periods for each zone during which slurry application is prohibited are as follows: zone A: 15 October to 12 January; zone B: 15 October to 15 January; and zone C: 15 October to 31 January.

2.2.2. Risks of losses to watercourses

The risks of nutrient transport through run-off or leaching are well established, and need to be considered when determining the suitability of conditions for spreading slurry. Holden *et al.* (2007) described a method for incorporating the risks of run-off and leaching losses by defining a day as suitable for spreading slurry as one when no drainage or overland flow shall occur in the 2 days immediately after the application of slurry. Drainage was assumed to occur if the soil moisture deficit fell below zero. Overland flow was assumed to occur if the rainfall in 24 hours exceeds the infiltration rate of the soil. The calculation of soil moisture deficit in this model was based on the hybrid soil moisture deficit model developed by Schulte *et al.* (2005). A 2 day period after spreading during which no drainage or overland flow will occur is in keeping with the conclusions of Parkes *et al.* (1997). The risk of loss to watercourses was considered to be the same for all application methods.

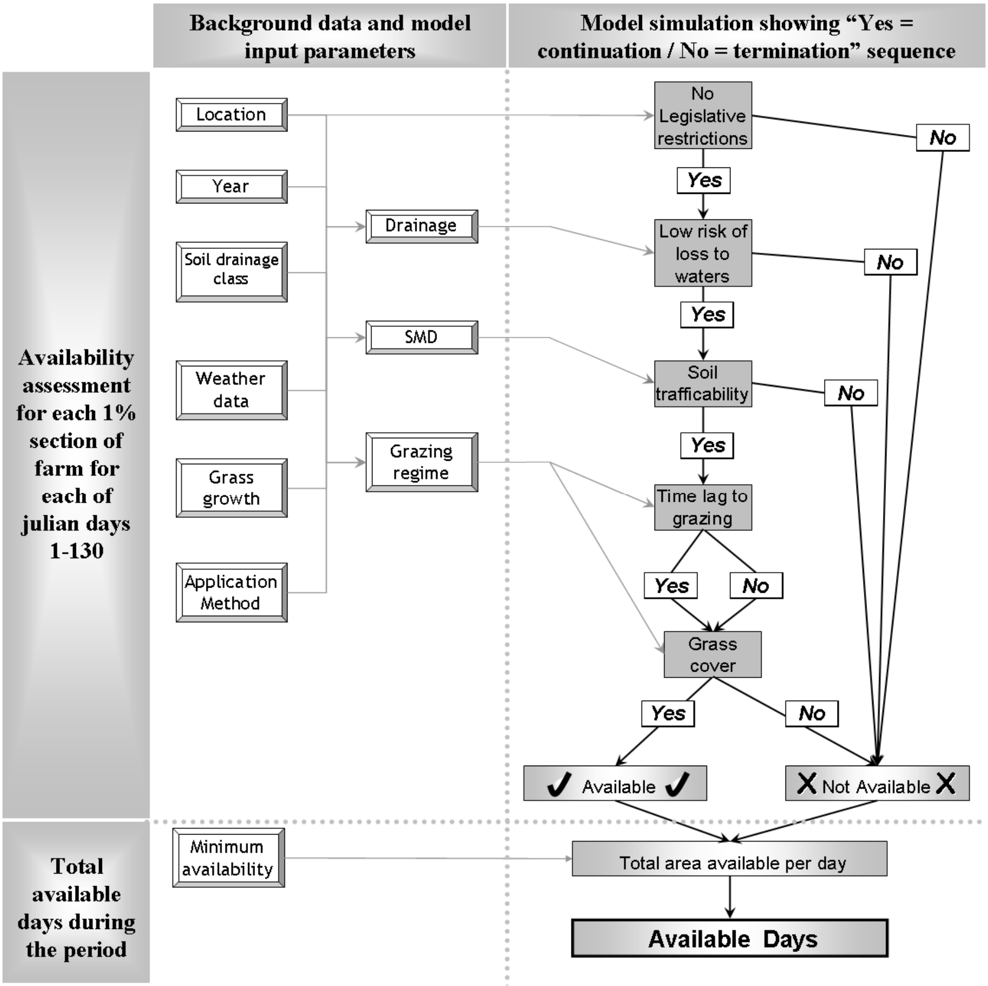

Figure 2.2. Diagrammatic representation of the model simulation sequence. A 'Yes' outcome indicates compliance with threshold criteria. A 'No' outcome indicates non-compliance.

2.2.3. Soil trafficking

Soil moisture deficit can be used as a crude predictor of soil trafficability. Earl (1997) estimated minimum thresholds of soil moisture deficit that allow damage free trafficking on grassland soils to be in the range of 5–15 mm, with a mean of approximately 10 mm. The different application systems have been shown to vary in terms of their draught power requirement (Huijsmans *et al.*, 1998; Rodhe *et al.*, 2004). In the absence of a quantitative relationship between draught power requirement and soil moisture deficit, all the application methods were assumed to have a minimum soil moisture deficit threshold of 10 mm. A sensitivity analysis was also conducted to examine the effect of setting a lower (5 mm) or higher (15 mm) minimum threshold.

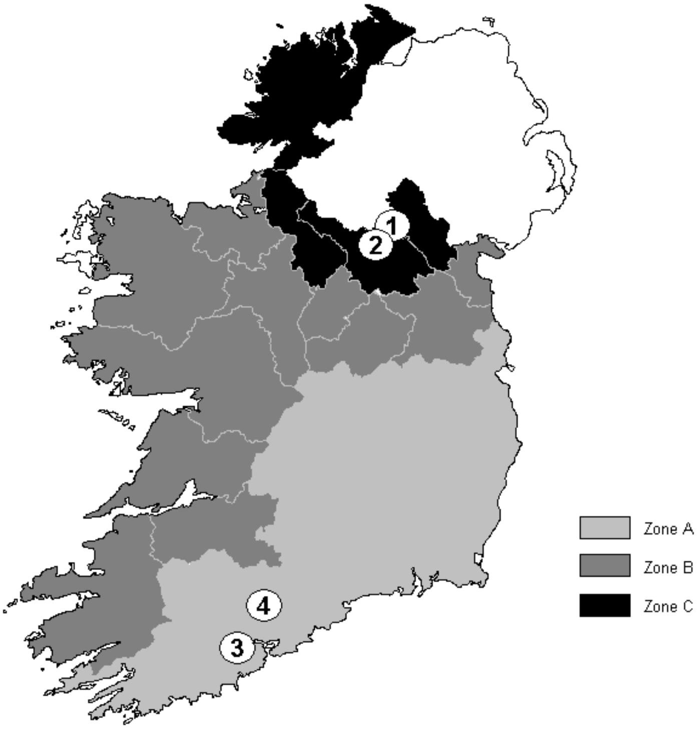

Figure 2.3. Map of Ireland showing the geographical division of zones adopted for Nitrates Directive legislation (zone A; zone B; and zone C), and the location of the data sources used for the model (1, Clones; 2, Ballyhaise; 3, Cork airport; and 4, Moorepark).

2.2.4. Soil moisture deficit and drainage

The soil moisture deficit and soil drainage parameters were calculated for each soil type, year and site using the model developed by Schulte *et al.* (2005). Occasional missing data (<0.01 of data set) were estimated by calculating the mean of the previous and subsequent days. The soil moisture deficit and drainage criteria were calculated for each day and soil type based on the weather data from the Met Éireann weather stations at Clones and Cork Airport for the period 1998 to 2005 (Anon, 2007b).

2.2.5. Time-lag before subsequent harvest

Studies of Laws and Pain (2002) and Laws *et al.* (2002) concluded that the period between slurry application and subsequent herbage removal by grazing or cutting determines the degree to which the slurry application affects rejection of herbage when grazing or silage quality. A time lag of approximately 42 days is generally considered to be required to avoid these effects (Humphreys *et al.*, 2007). Although this will also depend on the herbage mass above 4 cm at the time of application, a 42 day period should be sufficient irrespective of this herbage mass. However, applications of slurry to swards with greater herbage masses may result in reduced growth potential because of damage from trampling, thereby potentially counteracting the benefits in yield expected from the application of nutrients as slurry. An upper limit of 800 kg ha^{-1} DM was used in this model to reflect a herbage mass above 4 cm below which trampling of herbage will not result in excessive damage to the pasture or loss of subsequent yield.

The model assumes that all areas with a time-lag of greater than 42 days were available for spreading slurry, provided that the herbage mass above 4 cm was below 800 kg ha^{-1} DM. The availability of areas with a time lag of less than 42 days was determined by the herbage mass above 4 cm on the day of application. While rainfall in the period after application will reduce the risk of contamination of herbage (Laws *et al.*, 1996), it was not included as a factor in the model. Accurate long-range weather forecasting, that would predict rainfall for a minimum period of 2–3 weeks, would be required for a decision to be made prior to application of slurry to reduce the time lag based on rainfall after the application of slurry. However, since the 42 day time lag will be variable in practice, a sensitivity analysis was conducted to evaluate the effect of varying this period.

2.2.6. Herbage mass

The low-emission application methods (SI, TS and BS) allow more flexible timing of application than the SP method as slurry can be applied to pastures with higher herbage masses by depositing slurry below the herbage canopy, thereby minimizing contamination of herbage (Laws *et al.*, 2002). The maximum threshold of herbage mass for each application method was defined as the herbage mass above 4 cm, above which the model will not allow slurry application. The determination of the maximum threshold that is appropriate for each application method was based on the following rationale. The SP method has the lowest maximum threshold since the slurry will have contact with the entire spreading area (Misselbrook *et al.*, 2002). In the absence of heavy rain, herbage may retain some slurry on the foliage. A maximum threshold of 300 kg ha^{-1} DM above 4 cm was set to reflect the fact that the SP method is restricted to herbage masses equivalent to those immediately post-grazing or harvest (O'Donovan *et al.*, 2006). The TS method offers the greatest potential for contamination-free application in pastures with taller herbage (Laws and Pain, 2002; Laws *et al.*, 2002), and has been assigned the highest threshold. The TS method is designed so that the herbage is combed open, allowing the slurry to be deposited below the pasture and on top of the soil. While the actual direct contamination of herbage that occurs is minimised, the proportion of herbage that receives traffic from machinery wheels will be important, as the machinery cannot separate the grass canopy if it has already been flattened by the machinery wheels. To reflect that the machinery can apply slurry to pastures with a substantial herbage mass, while not overestimating the maximum threshold in order to avoid excessive trampling of herbage, the maximum threshold was set at 800 kg ha^{-1} DM. This maximum threshold for application using the TS method also corresponds with the upper threshold applied for all application methods when the time-lag before subsequent grazing or harvesting is greater than 42 days.

The BS and SI methods were assigned maximum thresholds intermediate to those for the SP and TS methods. Although the BS method reduces the potential for contamination compared with the SP method by slurry being applying in lines, it does not exclude contamination of herbage since the slurry is left on top of the herbage, rather than below it. The SI method also has an intermediate threshold. With this method, Laws *et al.* (2002) found that excessive disturbance to the herbage occurred at higher herbage masses. The maximum threshold for the SI method was set below that of the TS method as a result. The maximum thresholds of both the BS and SI methods were set at 600 kg ha^{-1} DM.

These maximum thresholds also reflect observations made from experiments in the UK (Laws *et al.*, 2002; K. A. Smith, *pers. comm.*). The impact of the herbage mass above 4 cm at the time of application is reduced as the time lag between slurry application and silage harvesting or grazing increases. The model assumes that the maximum threshold, which is specific to each application method, was only of consequence when the time lag was below 42 days.

2.2.7. Year, location and soil type

The model was run for 8 years (1998 to 2005). The model was simulated for two locations (Figure 2.3): (i) the north of Ireland (Clones), using herbage growth data collected at the Teagasc research farm at Ballyhaise, Co. Cavan (Anon, 2007a), and weather data from Clones, Co. Monaghan (Anon, 2007b); and (ii) the south of

Ireland (Cork), using herbage growth data collected at the Teagasc research farm at Moorepark, Fermoy, Co. Cork (Anon, 2007a), and weather data from Cork Airport (Anon, 2007b). In relation to compliance with legislative requirements for prohibited spreading periods, the Cork and Clones sites are located within zone A and zone C respectively. Meteorological data from the two sites for the study period (Table 2.2) show that the Clones site received on average 239 mm less rainfall annually than the Cork site. The mean annual air temperature and mean daily sunshine hours were 0.50°C and 0.6 h d^{-1} higher, respectively, at the Cork site than at the Clones site (Anon, 2007b). The length of the season of herbage growth was estimated to be approximately 300 days for the Cork site and 240–270 days for the Clones site (Collins and Cummins, 1996).

Table 2.2. Selected meteorological data for the Clones and Cork sites (Anon, 2007b). Values in brackets refer to minimum and maximum values.

Site	Period	Mean annual rainfall (mm)	Mean daily air temperature (°C)	Mean daily sunshine hours
Clones	1998-2005	957 (731 – 1186)	9.7 (9.2 – 9.9)	3.5 (3.1 – 3.9)
Cork	1998-2005	1196 (968 – 1538)	10.2 (10.0 – 10.4)	4.1 (3.7 – 4.7)

The model differentiated between three contrasting soil types on the basis of drainage. The classification of soils into well, moderately and poorly drained categories was in accordance with the classification system outlined by Schulte *et al.* (2005). The model assumed that the area of the dairy system falls into only one soil drainage class. There were six possible simulations for each application method within each year: two separate sites, each with three different soil drainage classes.

2.2.8. Herbage growth and grassland management

Herbage growth data, recorded at weekly intervals (Anon, 2007a), were used to plot a curve for each site in each year. In order to calculate daily growth rates of herbage to be used in the model, a linear model was used to calculate daily growth rates for days falling between the data points recorded weekly. A linear model was also used to calculate daily growth rates between 1 January and the first recorded growth rate in each year, with the growth rate on 1 January assumed to be 0 kg ha^{-1} d^{-1} of DM. Figure 2.4 shows the daily and cumulative herbage growth curves for each year and the mean grass growth curve for 1998–2005 at each site. Herbage growth rates were measured with an annual N application rate of 650 kg ha^{-1}, which corresponds to the total N load that a grazed pasture might receive from mineral fertiliser, and faeces and urine deposition. The plots on which these data are recorded were cut weekly and hence the application rate of N fertiliser reflects the total N input of a grazing system. The amount of N fertiliser applied also represents the potential grass growth from the sites.

In the simulations the area grazed on each day of the first grazing rotation was determined by the grassland management regime. The herbage mass on each day of each unit of the farm was calculated as the herbage mass on either 1 January or after previous grazing plus the accumulated subsequent herbage growth as determined from the herbage growth data. The range of herbage masses on 1 January in each year was assumed to be between 200 and 1000 kg ha^{-1} DM with a mean of 600 kg ha^{-1} DM. These values are in accordance with recommended grassland management systems for dairy farms in Ireland (Kennedy *et al.*, 2007). Each unit of the dairy cow system was assigned a herbage mass within this range and each unit grazed in descending order of herbage mass on 1 January.

For the purposes of grassland management in the spring period, the area of the dairy cow system was conceptually divided into two types of area. 'Silage area' refers to the area that, although it may be grazed in early spring, will become the area from which the harvest of first-cut silage will be made. The remainder of the grazing area will continue to be grazed while the silage area is removed from the grazing rotation. Grassland management regimes for each soil type at each location were based on dairy production blueprints for well-drained (O'Donovan, 2000; Shalloo *et al.*, 2004) and poorly-drained (O'Loughlin *et al.*, 2001; Shalloo *et al.*, 2004) soils. A regime for moderately drained soils was formulated as being intermediate of the blueprints for the well- and poorly-drained soils. Model inputs on grassland management were: (a) minimum and maximum herbage masses (200 and 1000 kg ha^{-1} DM respectively) on 1 January; (b) date of first grazing in spring; (c) silage area grazed or ungrazed in spring; (d) date of commencement of grazing of silage area in spring (if applicable); (e) proportion of grazing area that is grazed before silage area in the first rotation (if applicable); (f) date of final grazing of silage area (if applicable); (g) date of commencement of second grazing rotation; (h) number of days of second and subsequent grazing rotations; and (i) date of harvest of first-cut silage.

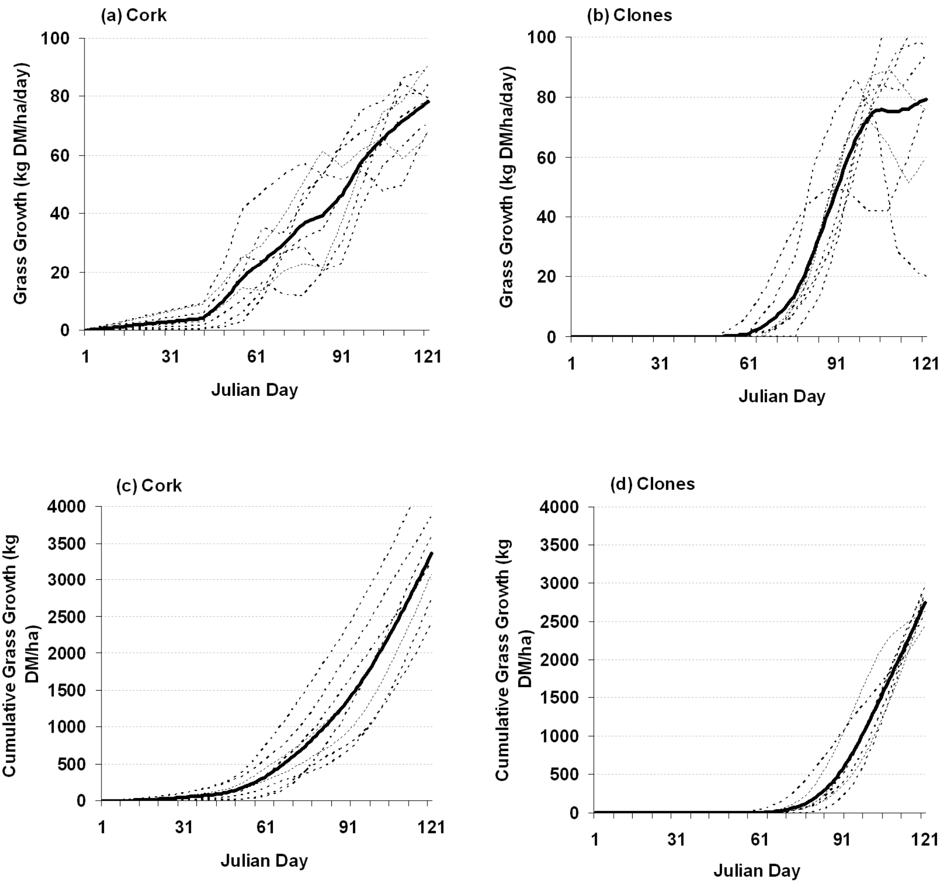

Figure 2.4. Mean herbage growth curve for the period from 1998 to 2005, based on herbage growth data from Moorepark (Cork) and Ballyhaise (Clones) (Anon, 2007a), showing (a) and (b) daily growth rates of herbage as a function of Julian days for the Cork and Clones sites respectively; and (c) and (d) cumulative herbage growth as a function of Julian days for the Cork and Clones sites respectively. Dotted lines refer to each year from 1998 to 2005. The solid line refers to the mean for the 8 years.

The grassland management systems used in the model for each location and soil type are shown in Table 2.3. The difference between the two sites was that the date on which the second grazing rotation should begin was estimated to occur later at the Clones site (20 April) than at the Cork site (15 April). The Clones site was assumed to be 4–7 days later for all other grazing or silage events as a result. As the length of the period of winter housing will be strongly linked to soil drainage, the percentage of the area harvested for silage increased from 45% on the well-drained soils to 52% on the poorly drained soils. Moreover, the beginning of the grazing season was later on the moderately-drained soils (11 March) than on the well-drained soils (19 February). However, both these soil types allow grazing of the area devoted to first-cut silage in the spring before the area was closed to allow growth of a silage crop. The later start of grazing on the poorly-drained soils (3 April) meant that the silage area was not grazed in the spring, and the rotation length was assumed to be 21 days from the start of grazing as a result. A post-grazing herbage mass of 200 kg ha^{-1} DM and a rotation length of 21 days for the second and subsequent rotation was assumed on all soil types (Kennedy *et al.*, 2007).

Table 2.3. Grassland management regimes for each location and soil type.

Site	Cork			Clones		
Soil Type	Well	Moderate	Poor	Well	Moderate	Poor
Proportion of area harvested for silage	0.45	0.48	0.52	0.45	0.48	0.52
Silage area grazed	Yes	Yes	No	Yes	Yes	No
Proportion of grazing area grazed before silage	0.3	0.3	-	0.3	0.3	-
Start of grazing	19 Feb	11 Mar	3 Apr	26 Feb	18 Mar	10 Apr
Start of grazing silage area	10 Mar	20 Mar	-	15 Mar	25 Mar	-
End of grazing silage area	1 Apr	1 Apr	-	5 Apr	5 Apr	-
Start of second grazing rotation	15 Apr	15 Apr	24 Apr	20 Apr	20 Apr	1 May
Date of silage harvest	23 May	22 May	21 May	27 May	26 May	25 May
Herbage mass post-grazing (kg ha^{-1} DM)	200	200	200	200	200	200
Rotation length of second and subsequent rotations (days)	21	21	21	21	21	21

2.2.9. Model output

The output produced from the model was the number of days during a specified period (Julian days 1 to 130) on which an amount of land ≥20% of the area of the dairy cow system was available for slurry application. The output was based on the specified minimum threshold criteria entered for each application method, as detailed in Table 2.1.

2.3. Results

The results for the median available days for spreading slurry by each application method in Julian days 1 to 130 of each year, when the minimum threshold criteria outlined in Table 1 were applied, are shown in Table 2.4. Values for the 10- and 90-percentile, i.e. the minimum number of days available in 9 of 10 years, and the maximum number of days reached once a decade, respectively, are also included.

Table 2.4. Median number of days during Julian days 0 to 130 annually for the years from 1998 to 2005 when ≥20% of the area was available for spreading slurry by each application method (SP, splash-plate; BS, band-spreader; TS, trailing shoe; and SI, shallow injection).

Soil Drainage Class	Site	Application Method			
		SP	BS	TS	SI
Well	Cork	2.0 (0.0 - 10.3)	3.0 (0.0 - 12.3)	8.0 (4.8 - 18.8)	3.0 (0.0 - 12.3)
	Clones	3.0 (0.0 - 13.1)	4.5 (0.0 - 14.7)	8.0 (2.1 - 15.9)	4.5 (0.0 - 14.7)
Moderate	Cork	0.5 (0.0 - 8.0)	1.0 (0.0 - 10.9)	6.5 (2.4 - 17.2)	1.0 (0.0 - 10.9)
	Clones	2.0 (0.0 - 9.6)	4.0 (0.0 - 15.0)	8.0 (2.1 - 15.6)	4.0 (0.0 - 15.0)
Poor	Cork	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 1.3)	0.0 (0.0 - 0.0)
	Clones	0.0 (0.0 - 3.3)	0.0 (0.0 - 3.3)	0.0 (0.0 - 3.3)	0.0 (0.0 - 3.3)

Values in brackets refer to 10- and 90-percentile range of days per year.

The highest median available days of all methods was the TS method on the well drained soil at both sites, and the moderately drained soil at the Clones site, where the median available days in the period were 8.0. The lowest available days occurred with the poorly drained soils, where the median available days at both sites was zero for all methods. The BS and SI methods showed identical results on all sites and soil types. This was anticipated since the threshold criteria for each method were the same.

On well drained soils, the TS method had the highest available days on both sites, although the advantage was greater at the Cork site (5.0 days higher) compared with the Clones site (3.5 days higher). The BS and SI methods had 1.0 and 1.5 days more available days compared with the SP method on the well-drained soils at the Cork and Clones sites respectively.

The results for the moderately-drained soils resembled those of the well-drained soils in that the TS method allowed the most available days particularly at the Cork site. The TS method at the Cork site had 5.5 more available days than the BS and SI methods. This compares with 4.0 days at the Clones site. The BS and SI methods had more available days on both sites than the SP method. The Cork and Clones sites had 0.5 and 2.0 more available days with the BS and SI methods than the SP method respectively. The poorly-drained soils showed no difference between application methods, as all methods showed zero available days at both sites.

Table 2.5 shows the number of years within the 8 year period wherein a minimum of 5 days were available for slurry application during Julian days 1–130 of each year. The minimum of 5 days was chosen to reflect what would be a reasonable opportunity to apply slurry where labour or contractor availability may be limiting. On poorly-drained soils, the presence of at least 5 available days occurred in only 1 of the 8 years at the Clones site. There was no year that allowed 5 available days at the Cork site. This was unaffected by the application method. The moderately drained soils had 5 or more available days in 2 or 3 years with the SP, BS and SI methods, while the TS method allowed a minimum of 5 available days in 6 years in the 8-year period. The well-drained soils showed a similar trend, with either 3 or 4 years with at least 5 available days with the SP, BS and SI methods, whereas the TS method allowed application in either 6 or 7 years within the 8-year period.

Table 2.5. The number of years within the 8 year period from 1998 to 2005 in which each application method (SP, splash-plate; BS, band-spreader; TS, trailing shoe; and SI, shallow injection) had a minimum of 5 days when ≥20% of the area was available for spreading slurry during Julian days 0 to 130.

Soil Drainage Class	Site	Application Method			
		SP	BS	TS	SI
Well	Cork	3	3	7	3
	Clones	3	4	6	4
Moderate	Cork	2	2	6	2
	Clones	2	3	6	3
Poor	Cork	0	0	0	0
	Clones	1	1	1	1

The median number of days on which the minimum soil moisture deficit and soil drainage thresholds are satisfied was strongly dependent on the soil drainage class. Table 2.6 shows that the well and moderately drained soils behaved similarly with a median number of days of 15.0 to 17.0 days with a soil moisture deficit greater than 10 mm, and 62.0 to 69.5 days with no drainage or overland flow for 2 days. By comparison, the poorly-drained soils had a median number of days of 5.5 to 6.0 days with a soil moisture deficit greater than 10 mm, and with no drainage or overland flow within 2 days of 15.5 to 24.0 days. On all soil types at all sites, soil trafficability was far more restrictive than the risk of loss to watercourses.

Table 2.6. Median number of days during Julian days 0 to 130 annually for the years from 1998 to 2005 when the dairy cow systems satisfied the minimum critical thresholds for soil moisture deficit (SMD) and occurrence of drainage or overland flow.

Soil Drainage Class	Site	SMD >10mm	No drainage / overland flow within 2 days
Well	Cork	15.0 (11.7 - 32.3)	65.0 (54.7 - 75.9)
	Clones	17.0 (5.0 - 39.8)	69.5 (56.7 - 76.9)
Moderate	Cork	15.0 (11.7 - 32.3)	62.0 (53.0 - 73.3)
	Clones	17.0 (5.0 - 39.8)	69.0 (55.7 - 75.0)
Poor	Cork	6.0 (2.4 - 17.5)	15.5 (11.4 - 36.8)
	Clones	5.5 (0.0 - 29.9)	24.0 (10.2 - 39.9)

Table 2.7. Median number of days during Julian days 0 to 130 annually for the years from 1998 to 2005 when ≥20% of the area was available for spreading slurry, using alternative combinations of minimum soil moisture deficit (SMD) and maximum herbage mass >4 cm thresholds.

Soil Drainage Class	Site	Minimum SMD threshold (mm)	Maximum herbage mass threshold (kg ha^{-1} DM) 200	300	400	500	600	700	800	900	1000
Well	Cork	5	10.0	10.0	10.0	10.0	11.0	13.5	21.0	27.0	27.5
		10	1.5	2.0 [a]	2.0	2.5	3.0 [b]	7.0	8.0 [c]	13.0	14.0
		15	0.0	0.0	0.0	0.0	0.5	1.0	3.0	6.0	6.5
	Clones	5	6.0	10.0	13.0	14.0	14.5	15.5	21.0	25.5	29.0
		10	0.0	3.0 [a]	4.0	4.0	4.5 [b]	6.0	8.0 [c]	11.0	13.0
		15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	5.0
Moderate	Cork	5	7.0	7.0	7.0	7.0	7.5	12.0	18.5	24.5	28.0
		10	0.5	0.5 [a]	0.5	0.5	1.0 [b]	3.5	6.5 [c]	12.0	13.0
		15	0.0	0.0	0.0	0.0	0.0	0.5	3.0	6.5	7.0
	Clones	5	6.0	6.0	10.0	14.0	15.5	15.5	22.5	25.5	30.5
		10	2.0	2.0 [a]	2.5	4.0	4.0 [b]	5.5	8.0 [c]	1.5	13.0
		15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	5.0
Poor	Cork	5	0.0	0.0	0.0	0.0	0.0	0.0	2.0	4.0	7.5
		10	0.0	0.0 [a]	0.0	0.0	0.0 [b]	0.0	0.0 [c]	1.5	3.5
		15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
	Clones	5	1.0	1.0	1.0	1.0	1.0	2.5	2.5	3.5	6.0
		10	0.0	0.0 [a]	0.0	0.0	0.0 [b]	0.0	0.0 [c]	0.0	1.0
		15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5

[a] denotes thresholds assumed in model for splash-plate application method
[b] denotes thresholds assumed in model for band-spreader and shallow-injection application methods
[c] denotes thresholds assumed in model for trailing shoe application method

The effect of varying the minimum soil moisture deficit and maximum herbage mass over 4 cm thresholds was also examined. Table 2.7 shows the effect that different values of minimum soil moisture deficit and maximum herbage mass would have on the model output of median available days per year. Earl (1997) found that the minimum soil moisture deficit threshold for damage-free soil trafficking on grassland ranged from 5 to 15 mm. Increasing the minimum soil moisture deficit threshold to 15 mm decreased the number of available days but the effect was greater on the well and moderately drained soils than on the poorly drained soils. Decreasing the minimum soil moisture deficit threshold to 5 mm increased the number of available days but the effect was greater on the well and moderately drained soils than on the poorly drained soils.

The effect of adjusting the maximum herbage mass threshold on the number of available days for any application method is shown in Table 2.7. The numbers of available days increase as the maximum herbage mass threshold increases although the effect is greater on the well and moderately drained soils than on poorly drained soils as the minimum soil moisture deficit threshold is the main restricting parameter on these soils.

Table 2.8. Median number of days during Julian days 0 to 130 annually for the years from 1998 to 2005 when ≥20% of the area was available for spreading slurry, using alternative thresholds of minimum time-lag before subsequent grazing or harvesting for the different methods of application (SP, splash-plate; BS, band-spreader; TS, trailing shoe; and SI, shallow injection).

Application method	Soil Drainage Class	Site	Minimum time-lag before subsequent grazing or harvesting event (days)					
			14	21	28	35	42 [a]	49
SP	Well	Cork	6.0	5.5	5.5	3.5	2.0	1.5
SP		Clones	5.0	4.0	4.0	3.0	3.0	2.0
SP	Moderate	Cork	5.0	4.0	2.0	4.0	0.5	0.0
SP		Clones	4.0	4.0	2.0	2.0	2.0	0.0
SP	Poor	Cork	0.0	0.0	0.0	0.0	0.0	0.0
SP		Clones	0.0	0.0	0.0	0.0	0.0	0.0
BS	Well	Cork	6.0	6.0	6.0	5.0	3.0	3.0
BS		Clones	5.5	5.5	5.5	4.5	4.5	3.5
BS	Moderate	Cork	5.0	5.0	3.5	1.5	1.0	1.0
BS		Clones	4.0	4.0	4.0	4.0	4.0	4.0
BS	Poor	Cork	0.0	0.0	0.0	0.0	0.0	0.0
BS		Clones	0.0	0.0	0.0	0.0	0.0	0.0
TS	Well	Cork	8.0	8.0	8.0	8.0	8.0	8.0
TS		Clones	8.0	8.0	8.0	8.0	8.0	8.0
TS	Moderate	Cork	6.5	6.5	6.5	6.5	6.5	6.5
TS		Clones	8.0	8.0	8.0	8.0	8.0	8.0
TS	Poor	Cork	0.0	0.0	0.0	0.0	0.0	0.0
TS		Clones	0.0	0.0	0.0	0.0	0.0	0.0
SI	Well	Cork	6.0	6.0	6.0	5.0	3.0	3.0
SI		Clones	5.5	5.5	5.5	4.5	4.5	3.5
SI	Moderate	Cork	5.0	5.0	3.5	1.5	1.0	1.0
SI		Clones	4.0	4.0	4.0	4.0	4.0	4.0
SI	Poor	Cork	0.0	0.0	0.0	0.0	0.0	0.0
SI		Clones	0.0	0.0	0.0	0.0	0.0	0.0

[a] denotes thresholds assumed in model

The minimum time lag required before a subsequent grazing or harvest event of 42 days that was adopted in this model may be more variable in practice. The effect of varying this threshold from 14 to 49 days is shown in Table 2.8. As the time lag threshold increases, the number of available days decreases for the SP, BS and SI application methods on the well and moderately drained soils. There was no effect on poorly drained soils with any application method. There was also no effect with the TS application method, since the maximum herbage mass threshold within the 42 day time lag period is equal to the maximum herbage mass that allows application of slurry outside the time lag period (800 kg ha^{-1} DM).

2.4. Discussion

All combinations of application method and site showed a decrease in the mean number of available days for slurry application as the soil-drainage class changed from well to moderate to poorly drained. The higher number of available days for the TS method compared with the other methods on the well and moderately drained soils was not found with the poorly drained soils. The decrease in available days on the poorly drained soils was due to the decreased number of days during which the soil moisture deficit threshold of 10 mm, and the soil drainage threshold of 2 days without drainage or overland flow, were satisfied. These results indicate that the number of available days for application of slurry in the spring, when efficiency of N use is assumed to be greatest (Coulter, 2004), is limited on poorly drained soils, irrespective of application method. The results also show that the number of available days with the SP method is not substantially higher on well or moderately drained soils. This supports the rationale behind the current slurry spreading patterns observed in Ireland whereby approximately 50% of slurry is applied in the summer months on silage aftermath using the SP method (Hyde and Carton, 2005).

The 10- to 90-percentile range of available days (Table 2.4) showed less variation between application methods than that observed with the median values. The 90-percentile value is an indicator of the number of available days to be expected in a ‘dry’ year, based on the data from 1998 and 2005 used in this study. When the 90-percentile number of available days is similar across application methods, such as with the poorly drained soils at both sites and the well drained soil at the Clones site, there is no advantage of one method over another in a ‘dry’ year. When the 90-percentile value varies between methods, a difference in performance in a ‘dry’ year can be concluded. The well and moderately drained soils at the Cork site both showed the TS method to allow 6 more available days in a dry year compared with the BS and SI methods and 9 more days compared with the SP method. The moderately drained soil at the Clones site showed no difference between the BS, TS and SI methods in a ‘dry’ year, but the number of days available with the SP method was 5 days less in a ‘dry’ year than with the other methods.

The 10-percentile value is an indicator of the number of available days to be expected in a 'wet' year, based on the data from 1998 and 2005. A 10-percentile value of zero occurred with almost all combinations of soil drainage, site and application method, with the only exceptions being the TS method on the well and moderately-drained soils at both sites. When the 10- percentile value was zero, it can be concluded that there would be no days available in a 'wet' year. Although the median days available show that the low-emission methods, particularly the TS method, generally did increase the number of days available for application of slurry in the spring. The risk that application of slurry in the spring remains impossible in some years is not negated completely by using low-emission methods rather than the SP method.

A minimum soil moisture deficit threshold of 10 mm (Earl, 1997) was used here as a crude indicator of soil trafficability. The relative advantage of the TS method is also based on the assumption that the soil moisture deficit threshold is common to all methods. The draught power requirements for the TS and SI methods are known to be greater than that of the BS or SP methods (Huijsmans *et al.*, 1998; Rodhe *et al.*, 2004). Moreover, the additional axle load as a result of the extra weight of the various additional attachments to the slurry tanker that are specific to each application method will also affect the soil trafficability threshold, and due consideration of weight and tyre specification should be a priority for machine manufacturers. It is not clear whether this difference could be overcome simply by increasing the power output of the tractor unit used to operate the TS or SI machinery, or whether the minimum soil moisture deficit threshold would also need to be higher in order to ensure damage-free soil trafficking. The effect of reducing or increasing the soil moisture deficit threshold by 5 mm did have an effect on the number of available days, particularly on the well and moderately drained soils with higher maximum herbage mass thresholds (800–1000 kg ha^{-1} DM) (Table 2.7). Further research is required to develop indicators of minimal-damage traffic conditions using each application method.

As the thresholds for soil moisture deficit, drainage and time lag required before harvesting or grazing are the same for each application method, it is the difference between the maximum herbage mass thresholds applied to each application method that determines the variation in the number of available days observed between methods. The relative advantage of the TS method, therefore, is based on the experience that it is the best machine for minimizing sward damage and contamination, and hence retains the highest maximum herbage mass threshold. This highlights the importance of equipment design so that the perceived advantages of the equipment are actually evident in operation. Issues, such as the proportion of the working width that receives trampling by tyres, or shoe coulter design in order to achieve effective sward separation, are critical in ensuring this.

Similarly, SI systems need to be designed to minimise soil disturbance and damage to herbage.

The output of the model assumes that the work rate of each application method will be equal, and that an available day will result in an equal amount of slurry being applied, irrespective of application method. A decision to convert to a low-emission application system on the basis of the number of available days in spring would also need to include comparisons of the work rate of the different application methods before assuming an advantage in terms of volume of slurry that can be applied in spring. Another consideration is labour availability in the spring so that spreading opportunities in the spring can be maximised.

2.5. Conclusions

By reducing the effect of slurry contamination of the herbage, the low-emission application methods, namely BS, TS and SI, offer more flexibility for application of slurry in spring compared to the more commonly used SP application method. This effect is strongly dependent on soil-drainage class and grassland management system. Well and moderately drained soils show a relatively large advantage with low-emission methods, whereas poorly drained soils show no appreciable difference between application methods. Of the low-emission application methods compared in this study, the TS method showed the largest advantage in terms of allowing the greatest number of available days for application of slurry in spring. Soil trafficking in the spring, however, remains a key constraint to optimizing the efficiency of utilisation of N in slurry through application to grassland in the spring. Further developments of application methods that reduce the adverse effects of soil trafficking will also allow greater opportunities for application of slurry to grassland in spring.

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3

Nitrogen fertiliser replacement value of cattle slurry in grassland as affected by method and timing of application

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Abstract

Slurry application with methods such as trailing shoe (TS) results in reduced emissions of ammonia (NH_3) compared with broadcast application using splash-plate (SP). Timing the application during cool and wet weather conditions also contributes to low NH_3 emissions. From this perspective, we investigated whether reduced NH_3 emissions due to improved slurry application method and timing results in an increase in the nitrogen (N) fertiliser replacement value (NFRV). The effects of application timing (June vs. April) and application method (TS vs. SP) on the apparent N recovery (ANR) and NFRV from cattle slurry applied to grassland were examined on three sites over 3 years in randomised block experiments. The NFRV was calculated using two methods: (i) $NFRV_N$ based on the ANR of slurry N relative to mineral N fertiliser; and (ii) $NFRV_{DM}$ based on DM yield. The TS method increased the ANR, $NFRV_N$, and $NFRV_{DM}$ compared with SP in the 40 to 50 day period following slurry application by 0.09, 0.10, and 0.10 kg kg^{-1}, respectively. These values were reduced to 0.07, 0.06, and 0.05 kg kg^{-1}, respectively, when residual harvests during the rest of the year were included. The highest $NFRV_{DM}$ for the first harvest period was with application in April using TS (0.30 kg kg^{-1}), while application in June with SP had the lowest (0.12 kg kg^{-1}). The highest $NFRV_{DM}$ for the cumulative harvest period was with application in April using TS (0.38 kg kg^{-1}), while application in June with SP had the lowest (0.17 kg kg^{-1}). Improved management of application method, by using TS instead of SP, and timing, by applying slurry in April rather than June, offer potential to increase the $NFRV_{DM}$ of cattle slurry applied to grassland.

3.1. Introduction

The high loss of nitrogen (N) through ammonia (NH_3) volatilisation following application to land often makes livestock slurries less efficient as a source of N for plants than mineral fertilisers (Schröder, 2005a). A wide range of estimates for N efficiency of slurry are reported internationally in both legislative and agronomic advice instruments. For example, Danish regulations specify that the N fertiliser replacement value (NFRV) of cattle slurry (i.e., the amount of mineral N fertiliser that can be replaced by slurry N) applied to grassland should be calculated as 0.70 kg kg^{-1} (Grant, 2009). This compares with lower targets of 0.45 to 0.60 kg kg^{-1} and 0.40 kg kg^{-1} set in nutrient regulations in The Netherlands and Ireland, respectively (Schröder and Neeteson, 2008; Anon, 2009). Agronomic advice in the United Kingdom (DEFRA, 2006) and Ireland (Coulter, 2004) proposes NFRV assumptions of 0.05 to 0.50 kg kg^{-1} and 0.05 to 0.25 kg kg^{-1}, respectively, depending on the method and timing of application. Current N recovery rates from slurry are not only low, but also highly variable, due to variations in slurry composition, application methods, spreading rates, soil and climatic conditions, and slurry N mineralisation rates (Schröder, 2005b). Pasture-based dairy and beef livestock systems dominate agricultural activity in Ireland. Animals are normally housed for a winter period, typically between 3 and 6 months in duration, during which grass conserved as silage usually dominates the diet. Approximately 80% of the manures produced during the winter period are managed as slurries, typically containing 70 g kg^{-1} dry matter (DM), 3.6 g kg^{-1} of total N, and 0.6 g kg^{-1} of total phosphorus (P). Approximately 50% of the total N in cattle slurry is in ammoniacal form. Broadcast application using tankers fitted with a splash-plate (SP) is the dominant application method in use in Ireland (O'Bric, 1991; Hyde *et al.*, 2006).

The low utilisation of N in slurry has commonly been attributed to the method and timing of its application. It has been well established that surface-broadcast application of slurry, using an SP, can be accompanied by high N losses through NH_3 volatilisation (Malgeryd, 1998; Mattila, 1998; Morken and Sakshaug, 1998; Smith *et al.*, 2000; Misselbrook *et al.*, 2002). In these comparative studies, NH_3 emissions were progressively reduced by using low-emission spreading techniques such as band spreading, trailing shoe (TS), and injection. The literature remains inconclusive about the magnitude of such reductions, since N utilisation and N losses depend on interactions between spreading techniques, grass cover, weather, and soil properties (Misselbrook *et al.*, 2002).

The losses of NH_3 following land application are affected by the weather and soil conditions such as air and soil temperature; relative humidity; solar radiation;

rainfall; and wind speed at the time of, and after, application (Sommer *et al.*, 1991; Moal *et al.*, 1995; Braschkat *et al.*, 1997; Genermont and Cellier, 1997; Menzi *et al.*, 1998; Sommer and Olesen, 2000; Sommer and Hutchings, 2001; Søgaard *et al.*, 2002; Misselbrook *et al.*, 2005). Observed seasonal and diurnal volatilisation patterns originate from these meteorological factors (Moal *et al.*, 1995; Sommer and Olesen, 2000; Reidy and Menzi, 2007). Agronomic advice in Ireland differentiates between spring (February to April) and summer (May to July) slurry application timings (NFRV = 0.25 and 0.05 kg kg^{-1}, respectively) on this basis (Coulter, 2004).

Although injection techniques offer the most potential for reducing NH_3 loss, they are not always suitable to permanent grassland systems, particularly where soils are stony. One of the low-emission spreading techniques that has been shown to be potentially advantageous on this type of grassland is the TS. The application of slurry in bands reduces the surface area of slurry exposed to the weather conditions that stimulate NH_3 volatilisation (Malgeryd, 1998; Mattila, 1998; Morken and Sakshaug, 1998; Smith *et al.*, 2000; Misselbrook *et al.*, 2002). In theory, since less NH_3 is volatilised, a higher proportion of N applied in slurry should be available to the grass crop, hence increasing the NFRV.

It has not yet been firmly established whether TS application increases utilisation of slurry N, translating into increased herbage production or reduced fertiliser N requirements. Some studies have reported that the utilisation of slurry N is increased with shallow (open-slot) injection and with surface banding techniques compared with broadcast application (Schils and Kok, 2003; Bittman *et al.*, 2005; Schröder *et al.*, 2007; Bhandral *et al.*, 2009), although results of increased N utilisation by the crop have been inconsistent in some experiments (Smith *et al.*, 2000; Laws *et al.*, 2002; Bittman *et al.*, 2005). Results from Northern Ireland suggest that TS applications may increase herbage mass by 21% compared with SP applications (Binnie and Frost, 2003). However, this increased utilisation had been dependent on grass cover, timing of application, and on the physical environment, that is, soil and weather conditions (Smith *et al.*, 2000; Misselbrook *et al.*, 2002). As a result, the NFRV of slurry applications has been difficult to predict. However, the lack of a significant N utilisation response to application method may often be due more to the difficulty in detecting an increase in the pool of crop available N from manure against a relatively large background release of N from the soil.

This study compares different calculation methods of NFRV based on N uptake and herbage yields relative to mineral N fertiliser, respectively. The effect of interactions between method and timing of application on slurry utilisation under Irish conditions is as yet poorly investigated. Such studies of NFRV are required for economic analyses of the costs and benefits of ammonia emission abatement. A series of experiments was hence performed to evaluate the effects of TS and SP application of slurry to grassland in April and June, to assess how the utilisation of N can be maximised.

3.2. Materials and Methods

3.2.1. Duration and Sites

The experiment was conducted over 3 years (2006-2008) on three permanent grassland sites dominated by perennial ryegrass (*Lolium perenne* L.): (i) a well-drained sandy loam to loam soil in Moorepark, Fermoy, County Cork (MP); (ii) a moderately well-drained loam soil in Johnstown Castle, Wexford (JC); and (iii) a poorly drained clay soil in Kilmaley, County Clare (KM) (Table 3.1). Within each site, a separate area was used each year to avoid inter-annual carryover effects. The area used in each year was used for grass silage with spring and autumn grazing in the preceding year.

Table 3.1. Treatment application and harvest dates for each treatment at each site in each year.

Year	Application timing	Site[a]	Date of slurry Application	Growth period: First harvest	Growth period: Cumulative harvests[b]
				——— days ———	
2006	June	MP	14-Jun	47	89 (2)
		JC	12-Jun	44	86 (2)
		KM	14-Jun	47	89 (2)
2007	April	MP	05-Apr	46	160 (3)
		JC	04-Apr	49	159 (3)
	June	MP	07-Jun	47	97 (2)
		JC	06-Jun	47	96 (2)
2008	April	MP	03-Apr	47	144 (3)
		JC	04-Apr	47	150 (3)
	June	MP	03-Jun	41	83 (2)
		JC	06-Jun	45	87 (2)

[a] MP = Well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare.

[b] Values in parenthesis represent the number of harvests taken during the cumulative period.

Weather data were collated from meteorological stations located on each of the study sites. The weather conditions recorded in the 24 hours following slurry applications are shown in Table 3.2. The mean air temperature, wind speed, and solar radiation following applications in April were 4.4°C, 0.4 m s^{-1}, and 401 J cm^{-2} lower, respectively, than for applications in June. Rainfall in the 24 hour period after application occurred in only two cases, both following June application in 2008 at the MP and JC sites.

Table 3.2. Weather conditions in the 24 hours following slurry application at each site in each year.

			Weather conditions in 24 hours following application				
Year	Application timing	Site[a]	Mean air temp	Mean wind speed	Rainfall	Relative Humidity	Cumulative Solar radiation
			°C	m s^{-1}	mm	%	J cm^{-2}
2006	June	MP	14.2	1.4	0.0	71	2275
		JC	14.4	3.1	0.0	80	1439
		KM	14.5	--[b]	0.0	73	--[b]
2007	April	MP	10.4	2.0	0.0	67	1916
		JC	7.9	2.0	0.0	74	1550
	June	MP	15.5	1.8	0.0	80	2238
		JC	13.0	3.0	0.0	79	2045
2008	April	MP	10.9	1.2	0.0	85	1465
		JC	8.9	3.1	0.0	82	1173
	June	MP	13.0	3.4	6.9	74	1626
		JC	12.6	2.5	1.1	80	1939
Mean weather conditions over all sites and years							
	April		9.5	2.1	0.0	77	1526
	June		13.9	2.5	1.1	77	1927

[a] MP = Well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare.

[b] Wind speed and solar radiation data were not available for the 'KM' site.

3.2.2. Experimental Design

The experiment was conducted at each site in each year as a randomised block design. Within each block, three treatments were applied: (i) control plots that received no slurry (control); (ii) broadcast application of slurry using SP; and (iii) band application of slurry at the soil surface using TS. A fourth treatment using TS application in a taller grass canopy was also included in the experimental design and data analysis of this study. The results of this treatment are reported separately in Chapter 4 of this thesis. The treatments were repeated for applications in early April and in early June. Each treatment had six replications, resulting in a total of 12 blocks per site per year (six blocks for April application and six blocks for June application). The experiment began in June 2006, and hence no application in April took place on any site in that year. Therefore, there were only six blocks per site in 2006, all receiving treatments in June. Slurry was applied to plots measuring 6 m by 3 m. The control plot was divided into six subplots measuring 6 m by 1.5 m, each of which received a different rate (0, 30, 60, 90, 120, or 150 kg ha^{-1} of N) of mineral N fertiliser as calcium ammoniacal nitrate (CAN). Blocks receiving treatments in June received 60 kg ha^{-1} of mineral N fertiliser, as CAN, in April and were harvested for silage in late May using conventional machinery. The herbage present on plots was cut to a height of 5 cm and removed before treatment application.

3.2.3. Slurry and Mineral Fertiliser Application

Slurry was applied to plots using a farm-scale 7600 litre slurry tanker and tractor. The tanker had a 6-m-wide boom fitted with 24 individual outlets at 25-cm spacing. The tanker had a positive displacement pump to ensure uniform slurry application rate. Each TS outlet was individually fed slurry from a rotary distribution unit via 40 mm diameter pipes, ensuring uniform distribution of slurry across the spreading width. To accommodate SP application, each TS outlet was modified to include an SP outlet. This method of broadcasting slurry was selected rather than a conventional single-outlet SP to guarantee uniform application across the spread width, and also to control the width of spreading. The tanker was also modified to allow onboard mixing and sampling of slurry. The same tractor, tanker, and operator were used in all years and sites. Dairy slurry was applied in all cases at a rate of 33 Mg ha^{-1}, equating to a target total slurry N application rate of 120 kg ha^{-1}. This rate of slurry was selected as being typical of the application rate applied annually to grassland in Ireland. This relatively high application rate of total slurry N was deliberate to ensure that any differences in crop response would be measurable and detectable.

The mineral N fertiliser was applied to the control treatment plots using a hand-operated 1.5 m wide fertiliser applicator. Blanket applications of mineral P, potassium (K), and sulphur (S) fertilisers were applied to each site before each slurry treatment application at rates of approximately 30, 250, and 40 kg ha^{-1}, respectively, depending on the soil fertility levels of each site. This was done to ensure that any yield response observed following the slurry treatments could not be attributed to nutrients other than N.

The dates of the slurry treatment applications are shown in Table 3.1. Treatment application at the KM site was confined to June 2006, due to the wet soil conditions on the poorly drained soil restricting machinery traffic in 2007 and April 2008, and a higher than anticipated presence of weed species in June 2008.

3.2.4. Sampling and Analysis

A 2 kg sample of slurry was taken from each tanker of slurry immediately before treatment application. The sample was collected following thorough mixing of the slurry, and stored at 4°C. Grass above 5 cm cutting height was harvested from the treatment plots using a Haldrup (Logstor, Denmark) plot harvester. Fresh yield of herbage was measured by the onboard weighing system. A 500 g herbage sample was collected and stored at 4°C for a maximum of 48 hours before analyses of DM and N concentration. Plots that received treatments in April were harvested a total of three times (May, July, and September), while plots that received treatments in June were harvested twice (July and September) (Table 3.1). No additional slurry or fertiliser amendments were applied to plots between harvests.

The DM concentration of slurry and grass was determined by drying at 105°C overnight. Total N concentration in slurry was determined by Kjeldahl digestion of fresh slurry. A subsample of the dried grass was milled through a 2 mm screen. Total N concentrations of the dried, milled grass samples were determined by Kjeldahl digestion. The DM yield and N uptake from each plot was then calculated for each plot on a Mg ha^{-1} and kg ha^{-1} basis, respectively.

3.2.5. Calculations and Statistical Analysis

The DM yield and N uptake for the first harvest was calculated and analyzed separately to that of the following harvests. To include the residual effects of slurry, the cumulative DM yield and N uptake of all the harvests were calculated. The relationships between DM yield and N uptake and fertiliser N application rate on the control treatments were modelled separately for each combination of site, year, and application timing, using the following quadratic plus plateau model (Eq. 3.1):

Eq. 3.1.

$$\begin{aligned} Y(N) &= a + bN + cN^2 , \quad && N < d \\ &= Y_{max} , && N \geq d \end{aligned}$$

where *Y* was either the DM yield (Mg ha^{-1}) or N uptake (kg ha^{-1}); *a* was the intercept (DM yield or N uptake at 0 kg ha^{-1} of mineral N fertiliser) (Mg ha^{-1} or kg ha^{-1}); *b* and *c* were the linear and quadratic coefficients, respectively; *d* was the join point of the curves (i.e., the fertiliser N rate above which the maximum DM yield or N uptake was obtained) (kg ha^{-1}) (Eq. 3.2); and *Ymax* was the maximum value of the response variable (Mg ha^{-1} or kg ha^{-1}) (Eq. 3.3):

Eq. 3.2. $$d = \frac{-b}{2c}$$

Eq. 3.3. $$Y_{max} = a - \frac{b^2}{4c}$$

The nonlinear regression analysis was implemented using PROC NLIN in SAS v9.1 (SAS, 2003). The DM yield and N uptake response to mineral N fertiliser was also modelled using a linear model. The selection of the quadratic plus plateau or linear model to describe each combination of site, year, and application timing was done on the basis of the highest coefficient of determination (pseudo R^2).

In the case of N uptake by the grass, parameter *a* of each response curve was taken as an estimate of the N uptake from the soil without mineral N fertiliser or slurry for each combination of site, year, and application timing (NU_{c0}) (kg ha^{-1}). The apparent N recovery (ANR_s) (kg kg^{-1}) of slurry N was calculated as (Eq. 3.4):

Eq. 3.4. $$ANR_s = \frac{NU_s - NU_{c0}}{NA_s}$$

where NU_s was the N uptake in harvested herbage from the slurry treatment (kg ha^{-1}) and NA_s was the total N applied in slurry (kg ha^{-1}). The NFRV was calculated by two separate methods. The NFRV based on the recovery of slurry N relative to that of mineral-fertiliser N ($NFRV_N$) (kg kg^{-1}) was calculated as (Eq. 3.5):

Eq. 3.5. $$NRFV_N = \frac{NA_{f=NUs}}{NA_s}$$

where $NA_{f=NUs}$ was the mineral N fertiliser application rate required to obtain an N uptake equivalent to that of the slurry treatment (kg kg^{-1}) and NA_s was the total N applied in slurry (kg ha^{-1}). The $NA_{f=NUs}$ for each slurry treatment replicate was estimated using the N uptake response curve specific to that combination of site, year, and application timing.

The NFRV based on DM yield ($NFRV_{DM}$) (kg kg^{-1}) was calculated as (Eq. 3.6):

Eq. 3.6. $$NRFV_{DM} = \frac{NA_{f=DMs}}{NA_s}$$

where $NA_{f=DMs}$ was the mineral-fertiliser N required to obtain a DM yield equivalent to that of the slurry treatment (kg ha^{-1}). The $NA_{f=DMs}$ for each slurry treatment replicate was estimated using the DM yield response curve specific to that combination of site, year, and application timing.

The effects of site, application timing, and application method, including all two-way and three-way interactions, on the N uptake, DM yield, ANR_s, $NFRV_N$, and $NFRV_{DM}$ of slurry were analyzed using mixed models, implemented using PROC MIXED in

SAS v9.1 (SAS, 2003). Application method, application timing, and site were included in the model as fixed effects. Year and block nested in site were included as random effects.

3.3. Results

3.3.1. Slurry Composition

The composition of the slurry used is shown in Table 3.3.

Table 3.3. Slurry composition data for each treatment at each site in each year.

Year	Application timing	Site[a]	Application method[b]	Slurry Composition: DM content	Total N content	NH_4-N content	Total N applied
				——— g kg^{-1} fresh		———	kg ha^{-1}
2006	June	MP	SP	78.0	3.92	1.74	130
			TS	75.3	4.39	1.68	145
		JC	SP	67.6	3.89	1.54	128
			TS	75.4	4.18	1.60	138
		KM	SP	79.3	4.12	1.68	136
			TS	79.1	4.00	1.72	132
2007	April	MP	SP	67.8	2.86	1.35	94
			TS	66.7	2.83	1.35	94
		JC	SP	61.2	2.83	1.42	94
			TS	60.5	2.87	1.45	95
	June	MP	SP	75.4	2.92	1.72	96
			TS	75.7	2.99	1.94	99
		JC	SP	67.7	2.81	1.39	93
			TS	68.0	2.94	1.83	97
2008	April	MP	SP	78.2	3.96	2.28	131
			TS	75.5	4.04	2.33	133
		JC	SP	75.7	2.90	2.08	96
			TS	77.2	3.05	2.12	101
	June	MP	SP	65.6	2.20	1.24	73
			TS	64.7	2.05	1.21	67
		JC	SP	74.1	2.03	1.28	67
			TS	73.2	2.16	1.26	71

[a] MP = Well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare.

[b] SP = broadcast application using splash-plate; TS = trailing shoe application.

The slurry DM content ranged from 60.5 to 79.3 g kg^{-1}. There was a considerable range in the total N content of the slurries used (2.03-4.39 g kg^{-1}) over the 3 yr of the experiment. However, the difference in total N content between slurries used for SP and TS treatments at each site and timing in each year was small, being ≤0.15 g kg^{-1} in nine of the 11 experiments. As a consequence of variability in total N content, there was also a considerable range in the application rate of total N in slurry (67-145 kg ha^{-1}). However, within each site, timing, and year, the difference between SP and TS was never >15 kg ha^{-1}, and was ≤6 kg ha^{-1} in nine of the 11 experiments.

3.3.2. Dry Matter Yield and Nitrogen Uptake

The parameter values of the nonlinear regression explaining the DM yield and N uptake for the first and cumulative harvests as a function of mineral N fertiliser application rate are shown in Table 3.4 (DM yield) and Table 3.5 (N uptake), and the curves are illustrated graphically in Figures 3.1 to 3.5.

At the first harvest, the JC site in April 2007 had the highest DM yield without mineral N fertiliser (*a*) (4.66 Mg ha^{-1}) and also had the lowest mineral N fertiliser required to obtain the maximum DM yield (*d*) (34.9 kg ha^{-1}). Conversely, the MP site in April 2008 had the lowest *a* (2.34 Mg ha^{-1}) and the highest *d* (156.0 kg ha^{-1}). The pseudo R^2 values for the regression were ≥0.5 in eight of the 11 experiments. The value of a for N uptake at the first harvest ranged from 41.5 kg ha^{-1} at the JC site in June 2006, to 79.4 kg ha^{-1} at the JC site in June 2007. The pseudo R^2 values for N uptake, ranging from 0.54 to 0.88, were higher in all cases than the pseudo R^2 values for DM yield.

For cumulative DM yield over all harvests, the JC site in April 2007 had the highest DM yield without mineral N fertiliser (*a*) (9.82 Mg ha^{-1}). The JC site in June 2006 had the lowest *a* (3.51 Mg ha^{-1}).

A linear function was chosen to describe the N uptake response to mineral N fertiliser in five of 11 site-application timing-year combinations (Table 3.5). The value of *a* for N uptake for cumulative harvests ranged from 64.1 kg ha^{-1} at the JC site in June 2006 to 177.9 kg ha^{-1} at the JC site in April 2007. For both DM yield and N uptake, the value of *d* was higher for cumulative harvests than for the first harvest, indicating a residual uptake of fertiliser N applied in the period after the first harvest.

Table 3.4. Parameter values of the non-linear regression explaining DM yield as a function of mineral N fertiliser application rate for each combination of year, application timing, and site.

				DM Yield					
Year	Application timing	Site[a]	Harvest[b]	*a*[c]	*b*	*c*	*d*[d]	*Ymax*[e]	Pseudo R^2
				Mg ha^{-1}			kg ha^{-1}	Mg ha^{-1}	
2006	June	MP	1	4.30	0.0167	-0.00006	140.0	5.47	0.20
			CUM	4.80	0.0172	-0.00001	665.5	10.51	0.42
		JC	1	2.77	0.0408	-0.00025	80.4	4.41	0.39
			CUM	3.51	0.0421	-0.00020	105.5	5.73	0.38
		KM	1	2.61	0.0396	-0.00015	135.3	5.29	0.77
			CUM	3.56	0.0436	-0.00015	142.9	6.68	0.71
2007	April	MP	1	3.62	0.0362	-0.00015	124.8	5.88	0.72
			CUM	7.31	0.0388	-0.00010	195.6	11.10	0.66
		JC	1	4.66	0.1123	-0.00161	34.9	6.62	0.43
			CUM	9.82	0.0493	-0.00017	141.1	13.30	0.45
	June	MP	1	3.20	0.0672	-0.00029	115.5	7.08	0.50
			CUM	5.47	0.0505	-0.00014	183.8	10.11	0.51
		JC	1	4.13	0.0961	-0.00093	51.5	6.61	0.53
			CUM	5.73	0.0946	-0.00075	63.1	8.72	0.55
2008	April	MP	1	2.34	0.0346	-0.00011	156.0	5.04	0.84
			CUM	6.34	0.0337	-0.00009	195.4	9.64	0.56
		JC	1	3.74	0.0489	-0.00023	106.3	6.34	0.77
			CUM	7.41	0.0508	-0.00015	164.6	11.59	0.67
	June	MP	1	2.40	0.0692	-0.00039	87.9	5.44	0.81
			CUM	3.76	0.0818	-0.00046	89.0	7.39	0.81
		JC	1	2.95	0.0348	-0.00011	153.4	5.62	0.80
			CUM	4.09	0.0432	-0.00017	129.0	6.87	0.78

[a] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare.

[b] 1 = first harvest; CUM = cumulative.

[c] *a* = DM yield at 0 kg ha^{-1} of mineral N fertiliser.

[d] *d* = join point of the curves (i.e. mineral N fertiliser rate above which max DM yield is obtained).

[e] Y_{max} = predicted maximum DM yield.

Table 3.5. Parameter values of the non-linear regression explaining N uptake as a function of mineral N fertiliser application rate for each combination of year, application timing, and site.

Year	Application timing	Site[a]	Harvest[b]	*a*[c]	*b*	*c*	*d*[d]	*Ymax*[e]	Pseudo R^2
				N uptake					
				kg ha^{-1}					
2006	June	MP	1	65.9	0.84	−0.00198	211.2	154.1	0.65
			CUM	80.2	0.86	–[f]	–[f]	–[f]	0.76
		JC	1	41.5	1.03	−0.00386	133.1	110.0	0.54
			CUM	64.1	1.18	−0.00369	159.8	158.2	0.48
		KM	1	47.0	0.99	−0.00173	286.9	189.4	0.80
			CUM	74.1	1.05	−0.00149	353.1	259.5	0.73
2007	April	MP	1	57.9	1.01	−0.00184	274.0	196.0	0.88
			CUM	142.9	0.90	–[f]	–[f]	–[f]	0.82
		JC	1	75.7	0.88	−0.00203	218.1	172.2	0.67
			CUM	177.9	1.11	−0.00130	425.7	414.3	0.59
	June	MP	1	69.2	1.05	−0.00165	319.4	237.0	0.56
			CUM	120.2	0.93	–[f]	–[f]	–[f]	0.55
		JC	1	79.4	1.40	−0.00502	139.6	177.1	0.69
			CUM	119.7	1.50	−0.00487	154.3	235.7	0.68
2008	April	MP	1	49.7	0.83	−0.00088	472.5	246.6	0.85
			CUM	141.9	0.80	–[f]	–[f]	–[f]	0.66
		JC	1	60.6	0.85	−0.00077	547.8	292.8	0.82
			CUM	130.4	0.98	–[f]	–[f]	–[f]	0.76
	June	MP	1	49.7	1.36	−0.00379	179.0	171.0	0.81
			CUM	88.7	1.49	−0.00372	200.6	238.4	0.79
		JC	1	47.5	0.88	−0.00128	343.7	198.9	0.83
			CUM	76.5	1.03	−0.00198	258.3	208.9	0.79

[a] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare.

[b] 1 = first harvest; CUM = cumulative.

[c] *a* N uptake at 0 kg ha^{-1} of mineral N fertiliser.

[d] *d* = join point of the curves (i.e. mineral N fertiliser rate above which max N uptake is obtained).

[e] Y_{max} = predicted maximum N uptake.

[f] Estimates for *c*, *d*, and Y_{max} do not exist for these curves as they are described by a linear response to mineral N fertilizer.

The relationship between N application, N uptake, and DM yield for first and cumulative harvests in each year and application timing combination at the MP, JC, and KM sites are shown in Figure 3.1 to 3.5. In all cases, the DM yields and N uptake following slurry treatments were lower than those predicted using mineral N fertiliser at equivalent N application rates. Over all experiments, the DM yield for the first harvest was 0.66 Mg ha^{-1} higher following slurry application with the SP method compared with the control treatment with no mineral N fertiliser (P <

0.001). This difference increased to 1.07 Mg ha^{-1} with cumulative harvests ($P < 0.001$). The DM yield was increased by an additional 0.39 Mg ha^{-1} with the TS method compared with SP for the first harvest ($P < 0.001$). The additional DM yield effect of TS over SP was smaller for cumulative harvests, being 0.22 Mg ha^{-1} ($P = 0.126$), indicating a greater residual effect following application with SP than with TS. The interaction of site and application timing also had a significant effect for the first harvest, with all sites and timings being similar, except for the April application at the JC site, where the DM yield was increased by 1.07 Mg ha^{-1} ($P = 0.002$). Over cumulative harvests, the interaction of site and application timing was significant ($P = 0.025$), with the JC site in April increasing yield by 0.93 Mg ha^{-1}. The interaction of application method and application timing was also significant for the cumulative harvests, with the difference between both SP and TS methods and the control treatment being higher with April application than with June ($P = 0.010$).

The N uptake in herbage in the first harvest was also affected by slurry application, being 19.0 kg ha^{-1} higher following slurry application with the SP method compared with the control treatment with no mineral N fertiliser ($P < 0.001$). The N uptake was increased by an additional 9.2 kg ha^{-1} with the TS method compared with SP ($P < 0.001$). The interaction of site and application timing was also significant ($P = 0.021$). The N uptake was 23.8 kg ha^{-1} higher with the April timing than with the June timing at the JC site ($P < 0.001$). It was 8.7 kg ha^{-1} higher with April application compared with June at the MP site, but the significance of this increase was marginal ($P = 0.058$). The N uptake with the June application timing was 10.1 kg ha^{-1} lower at the JC site than at MP ($P = 0.020$). There was no difference between the KM site and either JC or MP sites ($P = 0.887$ and 0.223, respectively). Over cumulative harvests, slurry application method ($P < 0.001$), application timing ($P < 0.001$), and site ($P = 0.001$) all had a significant effect on N uptake. However, no interactions of these factors were significant. The N uptake with the SP treatment was 24.2 kg ha^{-1} higher than the control treatment with no mineral fertiliser ($P < 0.001$). The N uptake with the TS treatment was 7.5 kg ha^{-1} higher than with SP ($P = 0.038$).

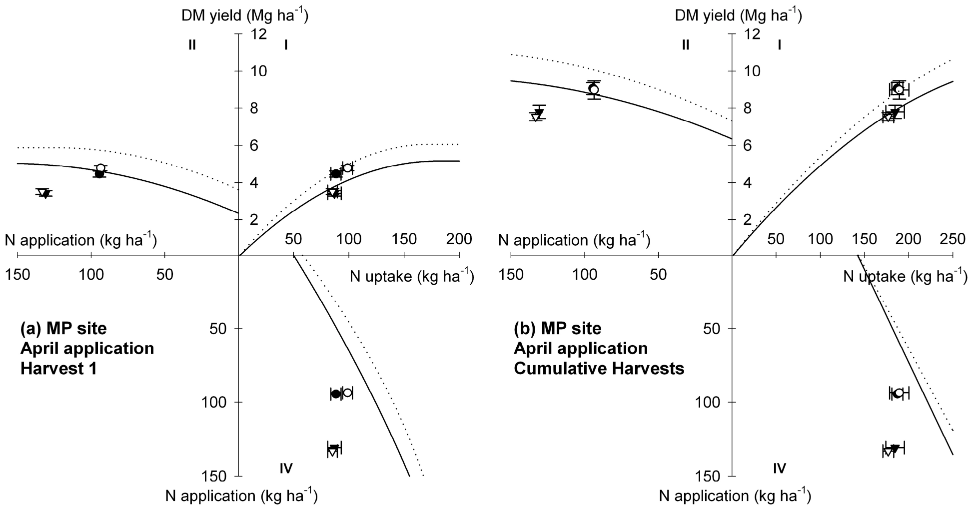

Figure 3.1. Relationship between N application, N uptake, and dry matter (DM) yield (in herbage above 5 cm) for mineral N fertiliser (• • • = 2007; — = 2008) and cattle slurry applied using splash-plate (solid: ● = 2007; ▼ = 2008) and trailing shoe (outline: ○ = 2007; ▽ = 2008) at the Moorepark (MP) site with April application for (a) the first harvest following treatment application, and (b) for cumulative harvests. Regression lines are fitted for mineral N fertiliser data. Error bars indicate SEM.

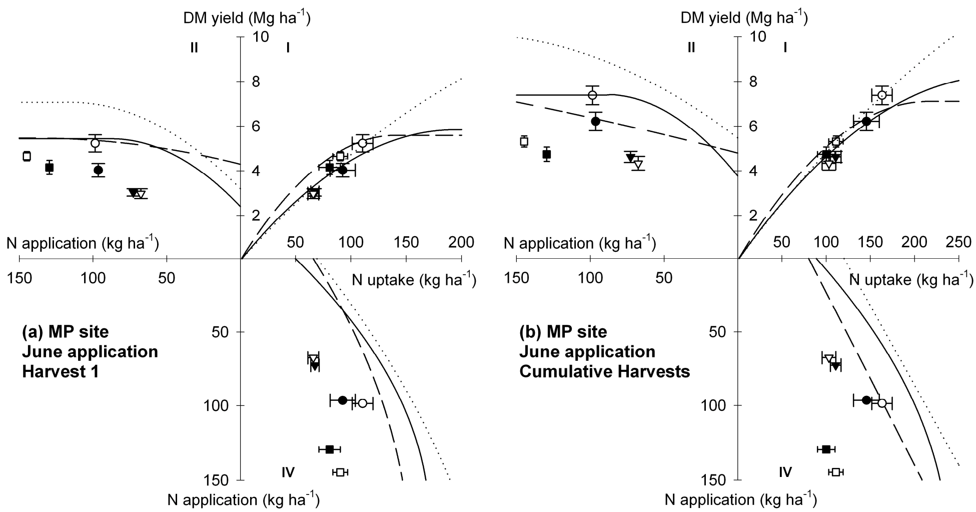

Figure 3.2. Relationship between N application, N uptake, and dry matter (DM) yield (in herbage above 5 cm) for mineral N fertiliser (- - - = 2006; • • • = 2007; — = 2008) and cattle slurry applied using splash-plate (solid: ■ =2006; ● = 2007; ▼ = 2008) and trailing shoe (outline: □ = 2006; ○ = 2007; ▽ = 2008) at the Moorepark (MP) site with June application for (a) the first harvest following treatment application and for (b) cumulative harvests. Regression lines are fitted for mineral N fertiliser data. Error bars indicate SEM.

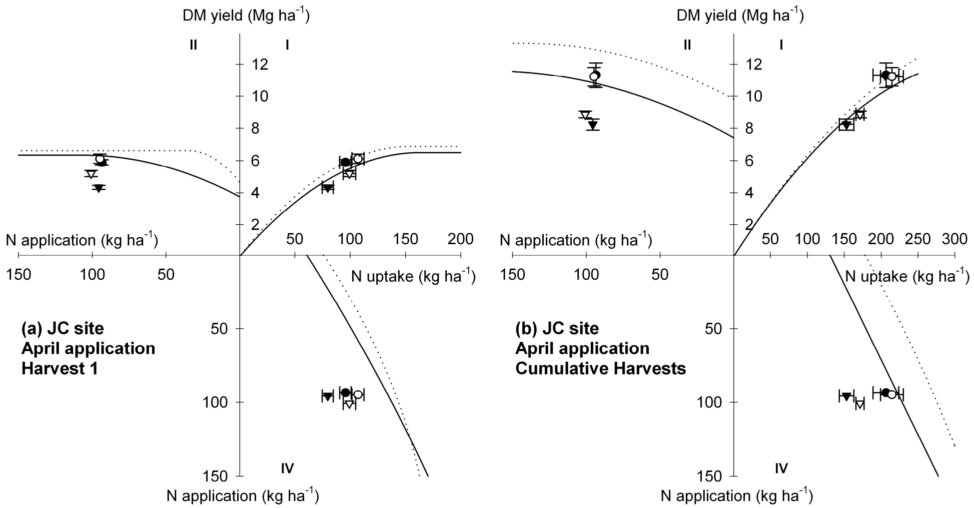

Figure 3.3. Relationship between N application, N uptake, and dry matter (DM) yield (in herbage above 5 cm) for mineral N fertiliser (··· = 2007; — = 2008) and cattle slurry applied using splash-plate (solid: ● = 2007; ▼ = 2008) and trailing shoe (outline: ○ = 2007; ▽ = 2008) at the Johnstown Castle (JC) site with April application for (a) the first harvest following treatment application, and for (b) cumulative harvests. Regression lines are fitted for mineral N fertiliser data. Error bars indicate SEM.

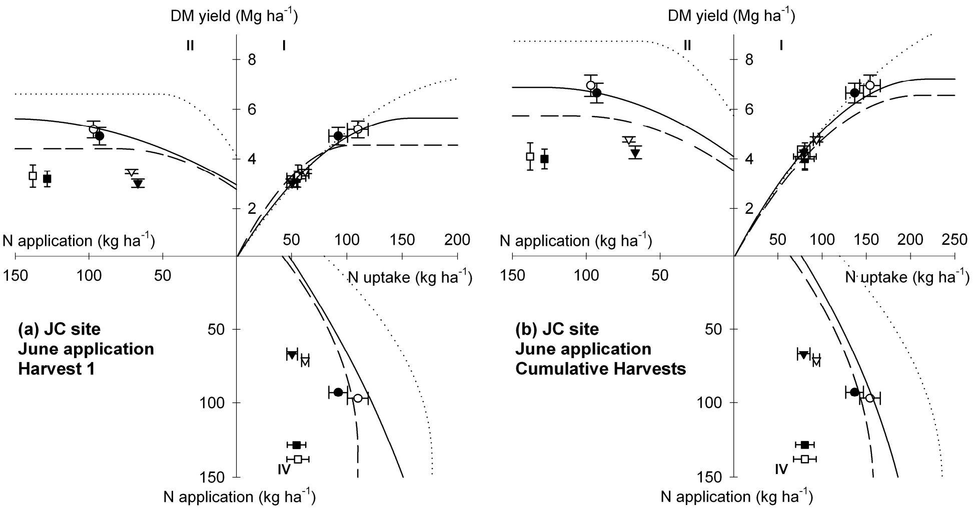

Figure 3.4. Relationship between N application, N uptake, and dry matter (DM) yield (in herbage above 5 cm) for mineral N fertiliser (- - - = 2006; ··· = 2007; — = 2008) and cattle slurry applied using splash-plate (solid: ■ =2006; ● = 2007; ▼ = 2008) and trailing shoe (outline: □ = 2006; ○ = 2007; ▽ = 2008) at the Johnstown Castle (JC) site with June application for (a) the first harvest following treatment application and for (b) cumulative harvests. Regression lines are fitted for mineral N fertiliser data. Error bars indicate SEM.

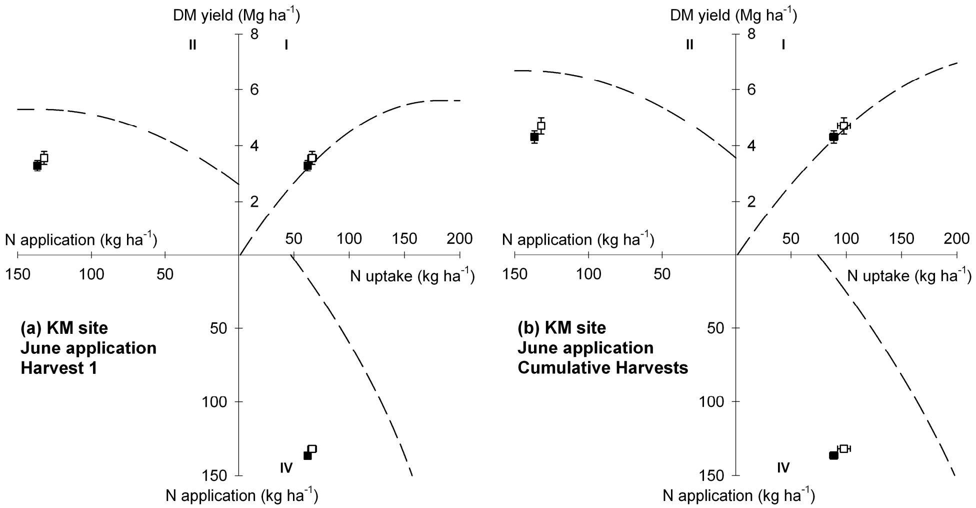

Figure 3.5. Relationship between N application, N uptake, and dry matter (DM) yield (in herbage above 5 cm) for mineral N fertiliser (- - -) and cattle slurry applied using splash-plate (solid: ■) and trailing shoe (outline: □) at the Kilmaley (KM) site in 2006 with June application for (a) the first harvest following treatment application and for (b) cumulative harvests. Regression lines are fitted for mineral N fertiliser data. Error bars indicate SEM.

3.3.3. Apparent Nitrogen Recovery

The ANR_S from slurry treatments for the first harvest, calculated for each site and for all sites combined, is shown in Figure 3.6. The ANR_S was significantly affected by slurry application method (P = 0.001), application timing (P < 0.001), and site (P = 0.003). The interaction of site and application timing was also significant (P = 0.007). The difference in ANR_S between SP and TS application methods was 0.09 kg kg^{-1} (P < 0.001), with TS being higher. The mean ANR_S was 0.13 and 0.15 kg kg^{-1} lower in June for the JC (P < 0.001) and KM (P = 0.003) sites, respectively, compared with the MP site. The mean ANR_S averaged over all sites and years was 0.25 and 0.16 kg kg^{-1} with SP, and 0.34 and 0.25 kg kg^{-1} with TS, in April and June, respectively. The ANR_S from slurry treatments for cumulative harvests is shown in Figure 3.7. The ANR_S was significantly affected by application timing (P = 0.007) and site (P = 0.001). The difference in ANR_S between April and June application timings was 0.09 kg kg^{-1}, with April being higher. The difference between SP and TS was 0.07, with TS being higher. However, the significance of this difference was marginal (P = 0.060). The mean ANR_S averaged over all sites and years were 0.26 and 0.17 kg kg^{-1} with SP, and 0.33 and 0.24 kg kg^{-1} with TS, in April and June, respectively. The ANR_S for the cumulative harvests were similar to those of the first harvest, indicating low uptake of total slurry N applied in the residual harvests.

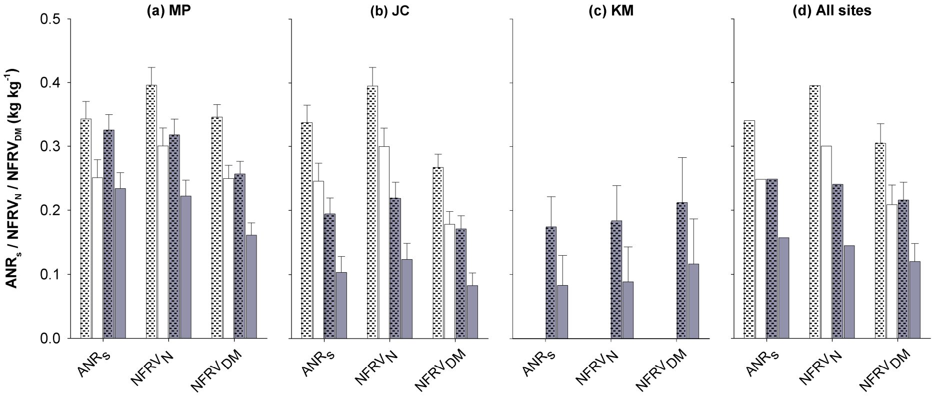

Figure 3.6. Apparent recovery of total slurry N applied (ANR_S), N fertiliser value based on N uptake ($NFRV_N$), and N fertiliser value based on dry matter yield ($NFRV_{DM}$) for the first harvest following treatment application with trailing shoe in April (white dotted bars), splash-plate in April (solid white bars), trailing shoe in June (shaded dotted bars), and splash-plate in June (solid shaded bars) at (a) Moorepark (MP), (b) Johnstown Castle (JC), (c) Kilmaley (KM), and (d) all sites over all years. Error bars indicate SEM.

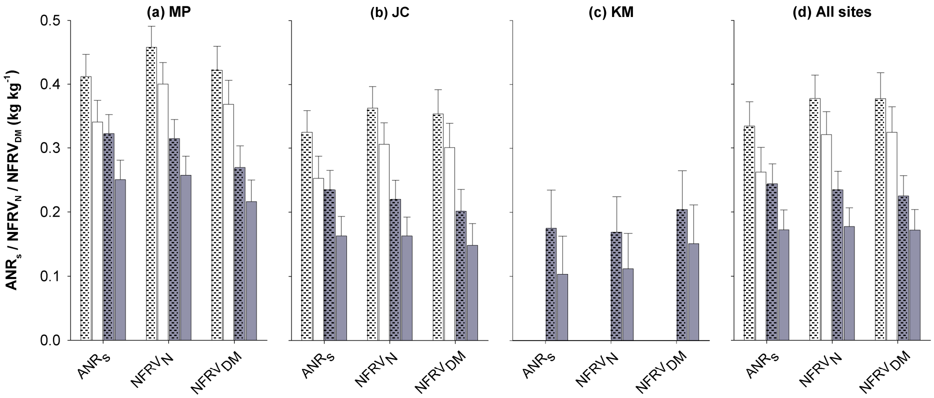

Figure 3.7. Apparent recovery of total slurry N applied (ANR_S), N fertiliser value based on N uptake ($NFRV_N$), and N fertiliser value based on dry matter yield ($NFRV_{DM}$), for cumulative harvests following treatment application with trailing shoe in April (white dotted bars), splash-plate in April (solid white bars), trailing shoe in June (shaded dotted bars), and splash-plate in June (solid shaded bars) at (a) Moorepark (MP), (b) Johnstown Castle (JC), (c) Kilmaley (KM), and (d) all sites over all years. Error bars indicate SEM.

3.3.4. Nitrogen Fertiliser Replacement Value

The $NFRV_N$ and $NFRV_{DM}$ from slurry treatments for the first harvest calculated for each site and for all sites combined are shown in Figure 3.6. The $NFRV_N$ for the first harvest was significantly affected by slurry application method (P = 0.002), application timing (P < 0.001), and site (P < 0.018). The interaction of site and application timing was also significant (P = 0.039). The difference in $NFRV_N$ between SP and TS application methods was 0.10 kg kg^{-1} (P < 0.001), with TS being higher. The $NFRV_N$ averaged over all sites and years were 0.30 and 0.14 kg kg^{-1} with SP, and 0.40 and 0.24 kg kg^{-1} with TS, in April and June, respectively. The MP site had the highest $NFRV_N$, being 0.13 kg kg^{-1} higher than the KM site (P = 0.020), and 0.10 kg kg^{-1} higher than the JC site (P < 0.001) in June. There was no difference between the JC and MP sites in April.

The $NFRV_N$ for the cumulative harvests was significantly affected by site (P < 0.001) and application timing (P < 0.001). Neither application method (P = 0.271) nor any interactions of these factors had a significant effect. The $NFRV_N$ averaged over all sites and years were 0.32 and 0.18 kg kg^{-1} with SP, and 0.38 and 0.23 kg kg^{-1} with TS, for the April and June application timings, respectively.

The $NFRV_{DM}$ for the first harvest was significantly affected by slurry application method (P < 0.001), application timing (P < 0.001), and site (P < 0.001). The significance of the interaction between site and application timing was marginal (P = 0.058). The $NFRV_{DM}$ with April application was 0.09 kg kg^{-1} higher than with June application (P < 0.001). The difference in $NFRV_{DM}$ between SP and TS application methods was 0.10 kg kg^{-1} (P < 0.001), with TS being higher. The mean $NFRV_{DM}$ averaged over all sites and years were 0.21 and 0.12 kg kg^{-1} with SP, and 0.30 and 0.22 kg kg^{-1} with TS, in April and June, respectively. The MP site had the highest $NFRV_{DM}$, being 0.08 kg kg^{-1} higher than JC, which had the lowest (P < 0.001). There was no difference in the $NFRV_{DM}$ between the KM site and either MP (P = 0.529) or JC (P = 0.633).

The $NFRV_{DM}$ for the cumulative harvests was significantly affected by application timing (P < 0.001), being 0.15 kg kg^{-1} higher with application in April than with that in June. The effect of site was not significant (P = 0.088). The TS application method increased the $NFRV_{DM}$ by 0.05 kg kg^{-1} compared with SP, but this increase was not significant (P = 0.158). The $NFRV_{DM}$ averaged over all sites and years were 0.32 and 0.17 kg kg^{-1} with SP, and 0.38 and 0.23 kg kg^{-1} with TS, for the April and June application timings, respectively.

3.4. Discussion

Application method had a significant effect on the DM yield, N uptake, ANR_s, $NFRV_N$, and $NFRV_{DM}$, with TS being higher than SP in all cases for the first harvest. The ANR_s, $NFNV_N$, and *$NFRV_{DM}$* with TS were 0.09, 0.10, and 0.10 kg kg^{-1} higher, respectively, than with SP for the first harvest. The difference between application methods was smaller for the cumulative harvests, being 0.07, 0.06, and 0.05 kg kg^{-1} for ANR_s, $NFRV_N$, and $NFRV_{DM}$, respectively. Therefore, the SP had higher residual N effects than TS in later cuts. While the ANR_s, $NFRV_N$, and $NFRV_{DM}$ varied with application timing and site, the increase with TS over SP remained consistent across sites and timings. While an increase with TS was expected on the basis of predicted reductions of ammonia emissions, a number of previous studies showed no significant response in DM yield from comparisons between SP and either surface banding or TS (Lorenz and Steffens, 1997; Smith *et al.*, 2000; Laws *et al.*, 2002; Rodhe and Rammer, 2002). Other studies, showing significant yield response include that of Bittman *et al.* (2005), where DM yield and N recovery were increased by approximately 11% with surface banding over aeration slots compared with SP. Studies by Schils and Kok (2003) and Schroder *et al.* (2007) showed an increase in the $NFRV_N$ in the year of application of approximately 0.18 and 0.15 to 0.17 kg kg^{-1}, respectively, with shallow injection compared with SP application methods. The increase in the mean $NFRV_N$ over all sites with TS compared with SP in our experiments was lower than the findings of these studies. However, the expected improvement in uniformity of application from using multiple outlet SPs may have enhanced the N utilisation following SP in this study compared with that which might be achieved in practice using conventional single-outlet SP equipment.

The results of this experiment relate to a growth period of only 80 to 160 days following application, and therefore do not account for residual effects from subsequent slurry N mineralisation in subsequent years. In a separate study using soil from the JC site used in this experiment, Hoekstra *et al.* (2009) estimated that when residual N release was taken into account, the total ANR of slurry was increased by 0.03 to 0.04 kg kg^{-1} by slurry N uptake during the second year after application. Of the initial slurry N applied, 0.30 kg kg^{-1} remained in the soil as a potential N mineralisation source after the end of the second year. Schroder *et al.* (2007) estimated cumulative ANR_s over 4 yr of 0.47 and 0.32 kg kg^{-1} for slurry applied using shallow injection and SP application methods, respectively. These equated to total $NFRV_N$ values over the 4 yr of 0.77 and 0.54 kg kg^{-1}, respectively. The $NFRV_N$ recovered between Years 2, 3, and 4 combined were 0.11 and 0.05 kg kg^{-1} for shallow injection and SP, respectively. Therefore, the residual effects of slurry application in subsequent years may result in long-term ANR_s, $NFRV_N$, and

$NFRV_{DM}$ values that are higher than those estimated for only the year of application. However, based on the results of the cumulative harvests in this study, the effect of application method on the long-term ANR_s, $NFRV_N$, and $NFRV_{DM}$ may be small.

The effect of site on ANR_s, $NFRV_N$, or $NFRV_{DM}$, while significant, was smaller than the effect of site on the total N uptake and DM yield. This may be explained by differences between sites in the N uptake with the control treatment at 0 kg ha^{-1} of mineral N fertiliser. The JC site, which had significantly higher DM yield with slurry application in April than all other site and application timing combinations, also had the highest DM yield at 0 kg ha^{-1} of mineral N fertiliser. Similarly, the JC and KM sites, which had lower N uptake with slurry application in June than the MP site in June, had lower N uptake at 0 kg ha^{-1} of mineral N fertiliser (Figures 3.1 to 3.5). The ANR_s, $NFRV_N$, and $NFRV_{DM}$ are calculated as net values having taken background N uptake, and resultant DM yields, into account. The presence of a significant effect of the interaction of site and application method or timing on ANR_s, $NFRV_N$, and $NFRV_{DM}$ indicates that the relative efficiency of slurry utilisation was not constant across sites. The variation in sites is mainly attributable to the higher ANR_s, $NFRV_N$, and $NFRV_{DM}$ at the MP site, particularly with June application timing, compared with JC or KM sites. The rainfall at the MP site in the 24 hours following application in June 2008 (Table 3.2) may have contributed to this. Further work is required to investigate the causes of this variation between sites.

When results for the first and cumulative harvests were averaged over all sites and years, the $NFRV_N$ was similar to ANR_s with application in June, and was higher than ANR_s with application in April (Figure 3.6d and Figure 3.7d). Where the $NFRV_N$ value is higher than ANR_s, it indicates that the apparent N recovery of mineral-N fertiliser is <1 kg kg^{-1}. Since the relationship between N uptake and mineral-N fertiliser was nonlinear, the apparent N recovery of mineral N fertiliser was not constant for all application rates of mineral N fertiliser. As the mineral-N fertiliser application rate increased, the marginal increase in N uptake, and hence the apparent N recovery of mineral N fertiliser, decreased (Figures 3.1 to 3.5). Since the N uptake from slurry application treatments was greater with application in April than in June, the apparent N recovery of mineral N fertiliser was lower in April than in June. This explains why the $NFRV_N$ was higher than the ANR_s in April but not in June.

When averaged over all sites and years, the $NFRV_{DM}$ for the first harvest was nominally lower than both ANR_s and $NFRV_N$ with all application method and timing combinations (Figure 3.6d). As with $NFRV_N$ with the June timing, the $NFRV_{DM}$ being lower than the ANR_s is a consequence of the DM yields of the slurry treatments being in the initial phase of the DM yield response curves, which show diminishing marginal DM yield increases to increasing mineral fertiliser N inputs. However, $NFRV_{DM}$ being lower than $NFRV_N$ indicates that the efficiency of N utilisation within the plant for DM production is lower with slurry N than with mineral N fertiliser. One explanation for this may be insufficient fertilisation rates of nutrients other than N. However, in this case, all plots received blanket applications of mineral P, K, and S fertilisers in line with grassland requirements. The additional P, K, and S supplied in the slurry would have further increased their supply to the grass in those treatments, making any deficiency unlikely. Another explanation of why $NFRV_{DM}$ was lower than $NFRV_N$ may be due to negative effects of slurry on DM yield, such as the effect of machinery wheel traffic potentially compromising the photosynthetic capacity and utilisation of the N taken up by the plants. No assessments of the effect of wheel traffic on either soils or herbage were undertaken in this study. However, Quadrant I of Figures 3.1 to 3.5 indicates that the DM yield at any given rate of N uptake were similar for slurry N and mineral N fertiliser. For cumulative harvests (Figure 3.7d), there was no difference between $NFRV_N$ and $NFRV_{DM}$. While the $NFRV_N$ for first and cumulative harvests are similar, the $NFRV_{DM}$ tended to increase. This indicates that, in the case of $NFRV_N$, the residual recovery of slurry N is equal to that of mineral N fertiliser. However, in the case of $NFRV_{DM}$, the efficiency of the residual N uptake for DM production in the residual period is higher than it is in the first growth period. This may be explained in part due to the negative effects of slurry on DM production already outlined. Further research comparing the N uptake and DM yield from both slurry and mineral N fertiliser is required to elucidate this relationship.

To use the results of this experiment to provide agronomic and policy advice, a decision is required as to whether $NFRV_N$ or $NFRV_{DM}$ is the most appropriate measure (Schröder, 2005b). Calculating $NFRV_N$ is useful when studying and describing N cycles and balances. However, $NFRV_{DM}$ has more practical relevance in an agronomic context, as DM yield is usually more critical than N uptake in farming systems, and hence is the main driver of N application rate decisions.

While the TS method had a higher $NFRV_{DM}$ than SP with both April and June application timings, the $NFRV_{DM}$ with the TS method in June was not significantly higher than with the SP method in April. However, in cases where a farmer is currently applying slurry with SP in June, but has soils suited to spring application, switching application from June to April with SP would have NFRV benefits equal to that of switching to TS application within the June timing. In Ireland in 2003, only 34% of slurry was applied in the spring (February to April) period (Hyde *et al.*, 2006), suggesting that the NFRV benefits of spring application were not fully exploited. However, not all soils are accessible for spring application due to soil trafficability or pasture contamination restrictions (Schulte *et al.*, 2006; Lalor and Schulte, 2008). While switching both application timing and method simultaneously would give the highest overall NFRV, the capacity within this strategy to recover the additional cost of TS application merits further investigation. Other methods for overcoming application timing restrictions due to soil trafficability, such as umbilical application systems that avoid heavy tanker traffic on fields, or systems for reducing ground pressure from machinery traffic, may also be beneficial and cost effective.

Surface banding, TS, and shallow or deep injection of slurries are accepted as key technologies for reducing NH_3 emissions from agriculture. Slurry application with SP is prohibited in most circumstances in Denmark and The Netherlands to meet ammonia emissions targets (Birkmose, 2009; Huijsmans and Schils, 2009). Expectations that the increased economic costs of using these technologies are fully recovered solely through fertiliser savings resulting from improved slurry N efficiency are questionable, and are highly dependent on prevailing economic conditions of machinery purchase and operational costs and fertiliser N price (Lalor, 2008). However, in addition to N efficiency benefits, there are other benefits of low-emission application methods, such as reduced odours, increased lateral distribution uniformity giving improved utilisation of all nutrients, reduced herbage contamination, and increased flexibility of application timing (Lalor and Schulte, 2008).

3.5. Conclusions

Application of cattle slurry to grassland using TS increased the ANR_s, $NFRV_N$, and $NFRV_{DM}$ compared with SP in the 40 to 50 day period following slurry application by 0.09, 0.10, and 0.10 kg kg^{-1}, respectively. These values were reduced to 0.07, 0.06, and 0.05 kg kg^{-1}, respectively, when residual harvests were included. Application of cattle slurry to grassland in April also gave similar increases in ANR_s, $NFRV_N$, and $NFRV_{DM}$ compared with application in June, although the extent of this increase was site dependent. The highest $NFRV_{DM}$ for the first harvest period was with application in April using TS (0.30 kg kg^{-1}), while application in June with SP had the lowest (0.12 kg kg^{-1}). The highest $NFRV_{DM}$ for the cumulative harvest period was with application in April using TS (0.38 kg kg^{-1}), while application in June with SP had the lowest (0.17 kg kg^{-1}). The use of $NFRV_{DM}$ is a preferred indicator of the agronomic efficiency of slurry use, as DM yield is the main driver of N application rate decisions on farms.

3.6. Acknowledgments

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4

Effect of application timing and grass height on the nitrogen fertiliser replacement value of cattle slurry applied with a trailing shoe application system

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Abstract

This study investigated the effect of using a trailing shoe system to apply cattle slurry, under different conditions of grass height (low (LG): freshly cut sward (4-5 cm height) vs. high (HG): application delayed by 7-19 days and applied to taller grass sward (4-11 cm) height) and month of application (June vs. April), on the nitrogen fertiliser replacement value (NFRV) and apparent N recovery (ANR_s) of cattle slurry applied to grassland. NFRV was calculated using two methods: (i) $NFRV_N$ based on the apparent recovery of slurry N relative to that of mineral N fertiliser; and (ii) $NFRV_{DM}$ based on DM yield. The effect of applying slurry into HG swards, relative to LG swards, decreased the DM yield by 0.47 Mg ha^{-1} ($P \leq 0.001$), N uptake by 5 kg kg^{-1} ($P = 0.05$), ANR_s by 0.05 kg kg^{-1} ($P = 0.036$), $NFRV_N$ by 0.05 kg kg^{-1} ($P = 0.090$) and $NFRV_{DM}$ by 0.11 kg kg^{-1} ($P < 0.001$). It was concluded that the main factor causing these decreases with HG, compared with LG applications, was wheel damage affecting subsequent N uptake and growth of the taller grass sward.

Keywords: cattle slurry, nitrogen, fertiliser, trailing shoe, apparent N recovery

4.1. Introduction

The nitrogen fertiliser replacement value (NFRV) of cattle slurry is known to be highly variable due to the effects of rate and timing of application, slurry placement and slurry composition (Schröder, 2005b). Livestock slurries are normally less efficient than mineral-fertilisers as a source of nitrogen (N) for plants, due to the high loss of N through ammonia (NH_3) volatilisation following their application to land, the initial unavailability of N in the organic fraction, and to lack of synchronisation between N supply and plant demand (Schröder, 2005a). Environmental policies relating to water, air and soil, such as the EU Nitrates Directive (Anon, 1991) National Good Agricultural Practice Regulations (Anon, 2010), and National Emissions Ceilings Directive (Anon, 2001), require manure management practices to reduce N-losses, with resultant increases in the replacement of mineral N fertiliser through improved utilisation of manures. It has been well established that surface-broadcast application of slurry, using a splash-plate system, can be accompanied by high N-losses through NH_3 volatilisation (Malgeryd, 1998; Mattila, 1998; Morken and Sakshaug, 1998; Smith *et al.*, 2000; Misselbrook *et al.*, 2002). In these comparative studies, NH_3 emissions were found to have been progressively reduced using low-emission spreading techniques, such as band spreading, trailing shoe and injection.

The literature remains inconclusive about the magnitude of such reductions in NH_3 volatilisation, because N-utilisation and N-losses depend on interactions between spreading techniques, grass canopy height, weather and soil properties (Sommer and Hutchings, 2001; Misselbrook *et al.*, 2002). Although injection techniques offer the greatest potential for reducing NH_3 emissions, they are not always suitable for permanent grassland systems, particularly on grassland with stony soils. The trailing shoe system is one of the low-emission spreading techniques shown to be potentially advantageous on this type of grassland. The application of slurry in bands reduces the surface area of slurry exposed to the weather conditions that stimulate NH_3 volatilisation (Malgeryd, 1998; Mattila, 1998; Morken and Sakshaug, 1998; Smith *et al.*, 2000; Misselbrook *et al.*, 2002). As less NH_3 is volatilised, a higher proportion of the N applied in slurry is available to the grass crop, hence increasing the NFRV. Some studies have reported that the utilisation of slurry N is therefore increased with shallow (open slot) injection and with surface-banding techniques compared with broadcast application (Binnie and Frost, 2003; Schils and Kok, 2003; Bittman *et al.*, 2005; Schröder *et al.*, 2007; Bhandral *et al.*, 2009; Lalor *et al.*, 2011). However, this increased utilisation is reported to depend on factors including grass cover, timing of application and the physical environment, that is, soil and weather conditions (Smith *et al.*, 2000; Misselbrook *et al.*, 2002; Webb *et al.*, 2010a).

In addition to a potential reduction in NH_3 emissions, another advantage of surface-banding methods is the flexibility in spreading opportunities that they provide by allowing application of slurry in taller grass swards without negatively affecting either silage quality or grazing preference (Laws and Pain, 2002; Laws *et al.*, 2002). Lalor and Schulte (2008) (Chapter 2 of this thesis) showed that by allowing application into taller grass swards, the surface-banding and injection methods allow more opportunity for application in the spring period, when the NFRV is usually highest due to weather conditions being more favourable for reduced NH_3 volatilisation. The height of the crop canopy at the time of application can also effect the emissions of NH_3 following slurry application by surface banding with either a trailing hose or trailing shoe. Emissions are reduced in taller canopies due to lower wind speed, leaf absorption and reduced temperature within the canopy (Sommer and Hutchings, 2001; Thorman *et al.*, 2008). Therefore, by permitting slurry application into taller grass swards, the trailing shoe technique has the potential to reduce NH_3 emissions for reasons of both improved application timing and sheltering, and NH_3 interception and absorption by the sward canopy.

As application into taller grass canopies is anticipated to reduce NH_3 emissions compared with application to low grass canopies or bare soil, the question arises as to whether the anticipated reduction in NH_3 loss translates into increased N uptake and NFRV. Therefore, the objective of this study was to compare the NFRV of cattle slurry applied to grassland using a trailing shoe technique under different conditions of grass height and application timing. The NFRV was expressed as kg of mineral N fertiliser that can be replaced by 1 kg of total N in slurry and hence is given as the units: kg kg^{-1}. The NFRV was calculated based on N uptake and on herbage yields relative to mineral N fertiliser. This study was conducted as part of a larger field experiment examining NFRV from cattle slurry application to grassland. A comparison of NFRV using trailing shoe and splash-plate application methods showed that cattle slurry applied using the trailing shoe method had an NFRV that was 0.10 kg kg^{-1} higher than the slurry applied with the splash-plate method under the same weather and grass sward-height conditions (Lalor *et al.*, 2011) (Chapter 3 of this thesis). This study and the findings reported here were conducted within the same experimental set-up.

4.2. Materials and methods

The experiment was conducted over 3 years (2006–2008) on three permanent grassland sites dominated by perennial ryegrass (Lolium perenne): (i) a well drained sandy loam to loam soil in Moorepark, Fermoy, Co. Cork (MP); (ii) a moderately drained loam soil in Johnstown Castle, Wexford (JC); and (iii) a poorly drained clay soil in Kilmaley, Co. Clare (KM) (Table 4.1). Within each site, a separate area was used each year to avoid inter-annual carry over effects. The area used in each year was used for grass silage with spring and autumn grazing in the preceding year.

Table 4.1. Treatment application and harvest dates for each treatment at each site in each year.

Year	Month of application	Site[a]	Grass height treatment[b]	Grass height[c]	Date of slurry application	Growth period: Single harvest	Growth period: Cumulative harvests[e]
				cm		——— days ———	
2006	June	MP	LG	5.0	14-Jun	47	89 (2)
			HG	7.9	28-Jun	33	75 (2)
		JC	LG	5.0	12-Jun	44	86 (2)
			HG	6.1	26-Jun	30	72 (2)
		KM	LG	5.0	14-Jun	47	89 (2)
			HG	6.0	28-Jun	33	75 (2)
2007	April	MP	LG	5.0	05-Apr	46	160 (3)
			HG	8.2	19-Apr	32	146 (3)
		JC	LG	5.0	04-Apr	49	159 (3)
			HG	9.1	17-Apr	36	146 (3)
	June	MP	LG	5.0	07-Jun	47	97 (2)
			HG	9.2	26-Jun	28	78 (2)
		JC	LG	5.0	06-Jun	47	96 (2)
			HG	11.1	25-Jun	28	77 (2)
2008	April	MP	LG	4.0	03-Apr	47	144 (3)
			HG	4.2	10-Apr	40	137 (3)
		JC	LG	4.0	04-Apr	47	150 (3)
			HG	5.7	14-Apr	37	140 (3)
	June	MP	LG	5.0	03-Jun	41	83 (2)
			HG	6.3	11-Jun	33	75 (2)
		JC	LG	5.0	06-Jun	45	87 (2)
			HG	5.8	16-Jun	35	77 (2)

[a] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare

[b] LG = application occurred after pre-treatment defoliation; HG = application was delayed and applied to taller grass sward

[c] Grass height measured using rising plate meter

[d] Values in parenthesis represent the number of harvests taken during the cumulative period

Weather data were collated from meteorological stations located at each study site. The weather conditions recorded in the 24 hours following slurry applications are shown in Table 4.2.

Table 4.2. Weather conditions in the 24 hours following slurry application at each site in each year.

					Weather conditions in 24 hours following application				
Year	Month of application	Site[a]	Grass height treatment[b]	SMD[c]	Mean air temp	Mean wind speed	Rainfall	Relative humidity	Cumulative solar radiation
				mm	°C	$m\ s^{-1}$	mm	%	$J\ cm^{-2}$
2006	June	MP	LG	55.0	14.2	1.4	0.0	71	2275
			HG	65.5	16.0	3.4	0.2	79	1412
		JC	LG	41.5	14.4	3.1	0.0	80	1439
			HG	51.9	12.2	2.3	2.7	91	235
		KM	LG	43.8	14.5	--[d]	0.0	73	--[d]
			HG	46.9	14.3	--[d]	4.6	88	--[d]
2007	April	MP	LG	29.8	10.4	2.0	0.0	67	1916
			HG	54.0	10.7	1.9	0.0	78	1671
		JC	LG	24.5	7.9	2.0	0.0	74	1550
			HG	43.9	9.7	2.1	0.0	72	1924
	June	MP	LG	48.6	15.5	1.8	0.0	80	2238
			HG	9.4	13.0	3.6	0.3	76	1675
		JC	LG	10.0	13.0	3.0	0.0	79	2045
			HG	-0.7	12.7	5.3	0.0	70	1931
2008	April	MP	LG	7.1	10.9	1.2	0.0	85	1465
			HG	16.6	5.8	5.1	4.1	78	1477
		JC	LG	8.8	8.9	3.1	0.0	82	1173
			HG	13.0	6.3	2.2	0.0	77	1681
	June	MP	LG	41.9	13.0	3.4	6.9	74	1626
			HG	49.6	14.0	3.7	0.8	85	1737
		JC	LG	7.8	12.6	2.5	1.1	80	1939
			HG	26.0	12.6	2.8	0.0	73	1831
Mean weather conditions over all sites and years									
	April				8.8	2.5	0.5	77	1607
	June				13.7	3.0	1.2	78	1699

[a] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare

[b] LG = application occurred after pre-treatment defoliation; HG = application was delayed and applied to taller grass sward

[c] Soil moisture deficit on the day of application, as predicted by model of Schulte *et al.* (2005)

[d] Wind speed and solar radiation data were not available for the KM site

The mean air temperature and wind speed following applications in the 2 years when slurry was applied in April were 4.9 and 0.5 m s^{-1} lower, respectively, than the corresponding mean values for the 3 years when slurry was applied in June. (These differences occurred by coincidence, as the application timings were not specifically timed to target specific weather conditions). Rainfall in the 24 hour period following application occurred in 8 of the 22 timings included. The soil moisture deficit (SMD) was estimated for each study site on the day of slurry application using the model developed by Schulte *et al.* (2005).

4.2.1. Experimental design

The experiment was conducted at each site in each year as a randomised block design. Within each block, three slurry treatments were applied: (i) no slurry application (control); (ii) band application of slurry at the soil surface using a trailing shoe method onto a low grass sward (LG); and (iii) slurry application using a trailing shoe method into a taller grass canopy (HG). The taller grass canopy for the HG treatment was created by delaying the slurry application; this delay allowed the grass canopy to grow between cutting and the time of slurry application. This treatment was designed to reflect the realistic situations that occur on farms, where, due to the effects of adverse weather on soil trafficability, there may be a delay in applying slurry after cutting or grazing. The length of time between LG and HG applications ranged from 7 to 19 days across all experiments. This resulted in a range of grass heights (4.2–11.1 cm) at the time of the HG application (Table 4.1). A fourth treatment, using broadcast application of slurry using a splash-plate, was also included in this study. The results of this treatment have been reported separately (Lalor *et al.*, 2011) (Chapter 3 in this thesis).

The treatments were repeated for applications made in 2 months: April and June. Each treatment had six replications, resulting in a total of twelve blocks per site per year (six blocks for April application and six blocks for June application). The experiment began in June 2006, and hence no application in April took place on any site in that year. Therefore, there were only six blocks per site in 2006, and these all received treatments in June. Slurry was applied to plots measuring 6 x 3 m. Nitrogen fertiliser plots that received no slurry were divided into six subplots measuring 6 x 1.5 m, each of which received a randomly allocated rate (0, 30, 60, 90, 120 or 150 kg ha^{-1} of N) of mineral N fertiliser as calcium ammonium nitrate (CAN), the timing of which corresponded to the LG slurry-treatment application. The subplot receiving 0 kg ha^{-1} was used as the control treatment for comparisons with the slurry treatments. Blocks receiving treatments in June received 60 kg ha^{-1} of mineral N fertiliser, as CAN, in April and were harvested for silage in late May using conventional machinery. The herbage on all plots was cut to a height of 5 cm (4 cm at the JC and MP sites in April 2008) and was removed during the week prior to the application of the LG slurry and mineral N fertiliser treatments. The grass height at the time of the HG treatment application was measured using a Filips rising plate meter (Jenquip, Feilding, New Zealand).

4.2.2. Slurry and mineral fertiliser application

Slurry was applied to plots using a farm-scale 7600 litre slurry tanker and tractor. The tanker had a 6 m wide boom fitted that had twenty four individual trailing shoes at 25 cm spacing. The tanker also had a positive displacement pump to ensure uniform slurry application rate. The application rate of the tanker was calibrated prior to the commencement of the experiment and rechecked annually by recording the time required to pump a known volume of slurry. Each trailing shoe outlet was individually fed slurry from a rotary distribution unit via 40 mm diameter pipes, ensuring uniform distribution of slurry across the spreading width. The tanker was modified to allow on-board mixing and sampling of slurry. The same tractor, tanker and operator were used in all years and sites. The consistency of the tractor forward speed during application between plots was monitored during plot application by recording the time taken to travel across each plot. Dairy slurry was applied in all cases at a rate of 33 Mg ha^{-1}, equating to a target total slurry N application rate of 120 kg ha^{-1}. This rate of slurry was selected as being typical of the application rate applied annually to grassland in Ireland and was sufficient to ensure that any differences in crop response would be measurable and detectable.

The mineral N fertiliser was applied using a hand-operated 1.5 m wide fertiliser applicator. Blanket applications of mineral phosphorus (P), potassium (K) and sulphur (S) fertilisers were applied to each site prior to each slurry treatment application, at rates of approximately 30, 250 and 40 kg ha^{-1} respectively. This was done to ensure that any yield response observed following the slurry treatments could not be attributed to nutrients other than N.

The dates of the slurry treatment applications are shown in Table 1. Treatment application at the KM site was confined to June 2006, due to the wet soil conditions on the poorly drained soil restricting machinery traffic in 2007 and April 2008 and a higher than anticipated presence of weed species in June 2008.

4.2.3. Sampling and analysis

A 2 kg sample of slurry was taken from each tanker of slurry immediately prior to treatment application. The sample was collected following thorough mixing of the slurry and stored at 4°C. Grass was harvested from the treatment plots using a Haldrup plot harvester (Haldrup, Løgstør, Denmark), the cutter bar of which was set to cut at a sward height of approximately 5 cm. Fresh yield of herbage was measured by the on-board weighing system. A 500 g herbage sample was collected from each plot and stored at 4°C for a maximum of 48 hours prior to analyses of dry matter (DM) and N concentration. Plots that received treatments in April were harvested three times (May, July and September), and plots that received treatments in June were harvested twice (July and September) (Table 4.1). No additional slurry or mineral fertiliser amendments were applied to plots between harvests.

The DM concentrations of slurry and grass were determined by drying at 105°C overnight. Total N concentration in slurry was determined by Kjeldahl digestion of fresh slurry. A subsample of the dried grass was milled through a 2 mm screen. Total N concentrations of the dried, milled grass samples were determined by Kjeldahl digestion. The DM yield and N uptake from each plot were then calculated for each plot on a Mg ha^{-1} and kg ha^{-1} basis respectively.

4.2.4. Calculations and statistical analysis

The DM yield and N uptake values for the first harvest following application were calculated and analysed separately from the cumulative DM yield and N uptake from all harvests combined. To include the residual effects of slurry, the cumulative DM yield and N uptake of all the harvests were calculated. The relationships between DM yield and N uptake and mineral N fertiliser application rate were modelled separately for each combination of site, year and month of application, using the methods and equations described by Lalor *et al.* (2011) (Chapter 3 of this thesis).

The apparent N recovery of slurry N (ANR_s) (kg kg^{-1}) was calculated as the N uptake in harvested herbage from the slurry treatment as a proportion of the total N applied in slurry (kg ha^{-1}). The NFRV was calculated by two separate methods. The NFRV based on the recovery of slurry N relative to that of mineral N fertiliser ($NFRV_N$) (kg kg^{-1}) was calculated as the mineral N fertiliser application rate required to obtain an N uptake equivalent to that of the slurry treatment as a proportion of the total N applied in slurry. The NFRV based on DM yield ($NFRV_{DM}$) (kg kg^{-1}) was calculated as the mineral N fertiliser required to obtain a DM yield equivalent to that of the slurry treatment as a proportion of the total N applied in slurry. The mineral N fertiliser required to obtain either the N uptake or DM yield equal to each slurry treatment replicate was estimated using the DM yield response curve specific to that combination of site, year and month of application. The equations used to calculate ANR_s, $NFRV_N$ and $NFRV_{DM}$ were those described by Lalor *et al.* (2011) (Chapter 3 of this thesis).

The effects of site, month of application and grass height, including all two-way and three-way interactions on the DM yield, N uptake, N concentration in herbage, ANR_s, $NFRV_N$ and $NFRV_{DM}$ of slurry were analysed using generalised linear mixed models, implemented using PROC MIXED in SAS v9.1 (SAS, 2003). Grass height, month and site were included in the model as fixed effects. Year and block nested in site were included as random effects. The covariance structure (unstructured, compound symmetry, autoregressive, heterogeneous compound symmetry or heterogeneous autoregressive) of the random effects in the model was optimised for each parameter using the restricted maximum likelihood method. The model was then reduced for fixed effects by sequentially removing non-significant ($P > 0.05$) effects using the maximum likelihood method. The optimised fixed model for each parameter was then used to estimate the predicted means and differences of each fixed effect included using the restricted maximum likelihood method.

The effects of the changes in estimated SMD and the measured grass height between LG and HG treatment applications on the difference in the mean ANR_s, $NFRV_N$ and $NFRV_{DM}$ of slurry for the first harvest following treatment application for each corresponding year, site and month of application combinations were analysed using generalised linear models, implemented using PROC GLM in SAS v9.1 (SAS, 2003).

4.3. Results

4.3.1. Slurry composition

The composition of the slurry used is shown in Table 4.3. The slurry DM content ranged from 59.1 to 80.5 g kg^{-1}. The total N content of the slurries ranged from 2.05 to 4.39 g kg^{-1} over the three years of the experiment, resulting in the application rate of total N ranging from 67 to 145 kg ha^{-1}. The ammonium N (NH_4-N) content of the slurries ranged from 1.21 to 2.33 g kg^{-1}, resulting in the application rate of NH_4-N ranging from 40 to 77 kg ha^{-1}. The NH_4-N content in slurry as a percentage of the total N content ranged from 38% to 70%, with a mean of 53%. The range of variability observed within the slurries used in this study was typical of the values commonly found in cattle slurries on Irish farms (O'Bric, 1991).

Table 4.3. Slurry composition data for each treatment at each site in each year.

Year	Month of application	Site[a]	Grass height treatment[b]	Slurry Composition: DM content	Total N content	NH_4-N content	Total N applied
				g kg^{-1} fresh			kg ha^{-1}
2006	June	MP	LG	75.3	4.39	1.68	145
			HG	72.3	4.32	1.75	143
		JC	LG	75.4	4.18	1.60	138
			HG	59.1	3.20	1.30	106
		KM	LG	79.1	4.00	1.72	132
			HG	76.9	4.29	1.69	142
2007	April	MP	LG	66.7	2.83	1.35	94
			HG	64.4	2.79	1.39	92
		JC	LG	60.5	2.87	1.45	95
			HG	64.5	2.76	1.39	91
	June	MP	LG	75.7	2.99	1.94	99
			HG	60.6	3.73	2.23	123
		JC	LG	68.0	2.94	1.83	97
			HG	64.5	3.59	1.72	119
2008	April	MP	LG	75.5	4.04	2.33	133
			HG	79.9	3.76	2.29	124
		JC	LG	77.2	3.05	2.12	101
			HG	69.0	2.86	1.90	94
	June	MP	LG	64.7	2.05	1.21	67
			HG	67.6	2.23	1.25	74
		JC	LG	73.2	2.16	1.26	71
			HG	80.5	2.18	1.29	72

[a] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare

[b] LG = application occurred after pre-treatment defoliation; HG = application was delayed and applied to taller grass sward

4.3.2. Dry matter yield and nitrogen uptake

The parameter values of the non-linear regression models estimating the DM yield and N uptake for the first and cumulative harvests as a function of mineral N fertiliser application rate were those described by Lalor *et al.* (2011) (Chapter 3 in this thesis). The response curves used were year, site and month of application specific. The DM yield, N concentration in herbage and N uptake following the control and slurry treatment applications in each year, month and site are shown in Table 4.4 and Table 4.5 for first and cumulative harvests, respectively.

Table 4.4. Mean herbage dry matter yield (DMY), N concentration in herbage (N conc), N uptake, apparent N recovery of slurry N (ANR_S), and N fertiliser replacement value of slurry based on N uptake ($NFRV_N$) and DM yield ($NFRV_{DM}$) for each grass height treatment, month of application, site, and year combination for the first harvest following treatment application.

	Grass height treatment [a]	2006			2007				2008				Significant Effects	
	Month	Jun			Apr		Jun		Apr		Jun			
Parameter	Site [b]	MP	JC	KM	MP	JC	MP	JC	MP	JC	MP	JC	Effect	P value
							Mg ha^{-1}							
DMY	Control	4.20	2.78	2.68	3.54	4.66	3.20	4.13	2.37	3.71	2.41	2.82	Site	< 0.001
	LG	4.66	3.31	3.57	4.78	6.12	5.23	5.19	3.52	5.19	2.98	3.49	Month	< 0.001
	HG	4.44	3.53	2.94	4.21	5.45	4.26	3.89	3.56	4.39	2.78	3.45	Grass	< 0.001
													Site*Month	0.002
							g kg^{-1}							
N conc	Control	15.5	14.4	19.0	16.4	16.1	20.3	18.6	21.5	17.3	19.9	17	Site	< 0.001
	LG	19.3	16.9	18.5	20.7	17.5	21.2	21.2	24.1	19.1	22.1	17.8	Grass	< 0.001
	HG	22.1	18.7	21.8	19.7	18.5	23.5	20.6	25.0	19.4	24.8	19.1	Grass*Site	0.017
							kg ha^{-1}							
N uptake	Control	65	40	51	58	75	65	77	51	64	48	48	Month	< 0.001
	LG	90	56	66	99	107	111	110	85	99	66	62	Grass	< 0.001
	HG	98	66	64	83	101	100	80	89	85	69	66	Site*Month	0.021
							kg kg^{-1}							
ANR_S	LG	0.20	0.11	0.15	0.45	0.34	0.41	0.31	0.23	0.39	0.32	0.20	Site	0.003
	HG	0.25	0.23	0.12	0.28	0.28	0.24	0.00	0.28	0.27	0.32	0.25	Month	< 0.001
													Grass	0.001
													Site*Month	0.007
							kg kg^{-1}							
$NFRV_N$	LG	0.27	0.14	0.16	0.49	0.42	0.42	0.25	0.29	0.49	0.25	0.23	Site	0.018
	HG	0.35	0.27	0.14	0.30	0.36	0.24	0.01	0.35	0.32	0.26	0.30	Month	< 0.001
													Site*Month	0.039
							kg kg^{-1}							
$NFRV_{DM}$	LG	0.30	0.21	0.21	0.43	0.17	0.37	0.15	0.26	0.37	0.16	0.22	Site	< 0.001
	HG	0.14	0.22	0.08	0.22	0.08	0.14	0.01	0.30	0.16	0.10	0.21	Month	< 0.001
													Grass	< 0.001

[a] LG = application occurred after pre-treatment defoliation; HG = application was delayed and applied to taller grass sward

[b] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare

Table 4.5. Mean herbage dry matter yield (DMY), N concentration in herbage (N conc), N uptake, apparent N recovery of slurry N (ANR_S), and N fertiliser replacement value of slurry based on N uptake ($NFRV_N$) and DM yield ($NFRV_{DM}$) for each grass height treatment, month of application, site, and year combination for cumulative harvests.

Parameter	Grass height treatment [a]	Month / Site [b]	2006 Jun MP	2006 Jun JC	2006 Jun KM	2007 Apr MP	2007 Apr JC	2007 Jun MP	2007 Jun JC	2008 Apr MP	2008 Apr JC	2008 Jun MP	2008 Jun JC	Significant Effects: Effect	P value
			Mg ha^{-1}												
DMY	Control		4.69	3.49	3.66	7.20	9.39	5.33	5.73	6.37	7.24	3.77	4.04	Month	< 0.001
	LG		5.31	4.09	4.70	8.97	11.20	7.38	6.95	7.54	8.87	4.34	4.78	Grass	< 0.001
	HG		5.16	4.37	3.95	8.15	10.60	6.53	5.75	7.86	7.78	4.31	4.79	Site*Month	0.025
														Grass*Month	0.01
			g kg^{-1}												
N conc	Control		17.4	17.7	21.6	19.6	18.3	21.8	20.2	22.3	18.5	22.5	19.5	Site	< 0.001
	LG		20.9	19.7	20.8	21.1	19.2	22.1	22.2	23.5	19.3	23.7	19.6	Grass	< 0.001
	HG		23.4	21.1	23.0	20.6	19.6	23.4	21.6	24.0	19.4	25.8	20.7	Month	< 0.001
														Site*Month	0.031
			kg ha^{-1}												
N uptake	Control		82	62	79	141	172	116	116	142	134	85	79	Site	0.001
	LG		111	81	98	189	215	163	154	177	171	103	94	Month	< 0.001
	HG		121	92	91	168	208	153	124	189	151	111	99	Grass	< 0.001
			kg kg^{-1}												
ANR_S	LG		0.26	0.12	0.18	0.50	0.39	0.43	0.35	0.23	0.43	0.28	0.21	Site	< 0.001
	HG		0.33	0.27	0.12	0.28	0.34	0.26	0.03	0.35	0.24	0.36	0.28	Month	0.007
			kg kg^{-1}												
$NFRV_N$	LG		0.30	0.15	0.18	0.56	0.39	0.47	0.27	0.29	0.44	0.20	0.21	Site	< 0.001
	HG		0.39	0.27	0.13	0.31	0.38	0.28	0.03	0.43	0.25	0.26	0.33	Month	< 0.001
			kg kg^{-1}												
$NFRV_{DM}$	LG		0.29	0.20	0.23	0.56	0.35	0.45	0.18	0.25	0.34	0.14	0.23	Month	< 0.001
	HG		0.22	0.24	0.09	0.27	0.19	0.19	0.02	0.37	0.14	0.12	0.24	Grass	0.022

[a] LG = application occurred after pre-treatment defoliation; HG = application was delayed and applied to taller grass sward

[b] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare

Over all experiments, the predicted mean DM yield for the first harvest was 1.05 Mg ha^{-1} higher following slurry application to the LG treatment compared to the control treatment ($P < 0.001$). The predicted difference was increased to 1.29 Mg ha^{-1} with cumulative harvests ($P < 0.001$), indicating a residual effect of slurry application on DM yield at subsequent harvests. The predicted DM yield was decreased by 0.47 Mg ha^{-1} with the HG treatment compared to LG at both the first and cumulative harvests ($P \leq 0.001$). The HG treatment increased the N concentration in herbage relative to the LG treatment by 1.6 g kg^{-1} ($P < 0.001$) for the first harvest and by 0.9 g kg^{-1} ($P = 0.005$) over cumulative harvests. The predicted mean N uptake in herbage over all experiments was 28 and 32 kg ha^{-1} higher following slurry application to the LG treatment compared to the control treatment with no mineral N fertiliser for the first and cumulative harvests, respectively ($P < 0.001$). Despite the N concentration in herbage being higher with HG treatment, the reduction in DM yield resulted in the predicted mean N uptake being decreased by 5 kg ha^{-1} with the HG treatment compared to LG at the first harvest ($P = 0.05$) and over cumulative harvests ($P = 0.209$).

4.3.3. Apparent nitrogen recovery and nitrogen fertiliser replacement value

The ANR_s, $NFRV_N$, $NFRV_{DM}$ from slurry treatment applications in each year, month of application and site are shown in Table 4.4 and Table 4.5 for the first and cumulative harvests, respectively. The predicted difference in the mean ANR_s, $NFRV_N$ and $NFRV_{DM}$ between individual grass height treatments, months of application and sites, and the significant interactions of these effects are shown in Table 4.6.

The ANR_s from slurry treatments for the first harvest was significantly affected by site ($P = 0.003$), month of application ($P < 0.001$) and grass height ($P = 0.001$). The interaction of site and month of application was also significant ($P = 0.007$), with the MP site showing the highest ANR_S overall, and no significant difference between application in April and June. The predicted mean ANR_s over all sites, months of application and years was 0.34 and 0.25 kg kg^{-1} for LG, and 0.29 and 0.20 kg kg^{-1} for HG, for applications in April and June, respectively (Figure 4.1a). The predicted mean decrease in ANR_s was 0.05 kg kg^{-1} for HG, relative to LG, slurry treatments ($P = 0.036$). The predicted mean ANR_s over cumulative harvests averaged over all sites, months of application and years was 0.33 and 0.24 kg kg^{-1} for LG, and 0.29 and 0.20 kg kg^{-1} for HG, in April and June, respectively (Figure 1a). The predicted mean ANR_s was 0.09 kg kg^{-1} lower for the June application than for the April application ($P = 0.007$). The HG treatment was 0.05 kg kg^{-1} lower than the LG treatment, but the predicted difference was not significant ($P = 0.203$).

Table 4.6. Predicted difference and SED in mean apparent N recovery of slurry N (ANR_S) and N fertiliser replacement value of slurry based on N uptake ($NFRV_N$) and dry matter yield ($NFRV_{DM}$) between grass height treatments, months of application, and sites for the first and cumulative harvests. (Data is absent where predicted differences were not estimable due to the interactions between factors being significant).

		ANR_S (kg kg^{-1})			$NFRV_N$ (kg kg^{-1})			$NFRV_{DM}$ (kg kg^{-1})		
		Predicted Difference	SED	P value	Predicted Difference	SED	P value	Predicted Difference	SED	P value
Harvest 1										
Grass Height[a]										
HG vs LG		-0.05	0.024	0.036	-0.05	0.027	NS	-0.11	0.024	< 0.001
Month of Applic.										
June vs. April								-0.09	0.019	< 0.001
Site[b]										
MP vs. JC								0.08	0.015	< 0.001
JC vs. K								-0.03	0.070	NS
MP vs. K								0.04	0.070	NS
Month of Applic. * Site										
April	MP vs. JC	0.01	0.034	NS	0.00	0.034	NS			
June	MP vs. JC	0.13	0.029	< 0.001	0.10	0.028	< 0.001			
	JC vs. K	0.02	0.049	NS	0.03	0.056	NS			
	MP vs. K	0.15	0.049	0.003	0.13	0.056	0.018			
MP	April vs. June	0.02	0.032	NS	0.08	0.032	0.017			
JC	April vs. June	0.14	0.032	<0.001	0.18	0.034	< 0.001			
Cumulative Harvests										
Grass Height[a]										
HG vs LG		-0.05	0.037	NS	-0.04	0.037	NS	-0.10	0.037	0.006
Month of Applic.										
June vs. April		-0.09	0.033	0.007	-0.14	0.032	< 0.001	-0.15	0.036	< 0.001
Site[b]										
MP vs. JC		0.09	0.024	< 0.001	0.10	0.024	< 0.001	0.07	0.031	0.033
JC vs. K		0.06	0.059	NS	0.05	0.060	NS	0.00	0.062	NS
MP vs. K		0.15	0.059	0.015	0.15	0.060	0.011	0.07	0.062	NS

[a] LG = application occurred after pre-treatment defoliation; HG = application was delayed and applied to taller grass sward

[b] MP = well drained soil, Moorepark, Co. Cork; JC = moderately drained soil, Johnstown Castle, Co. Wexford; and KM = poorly drained soil, Kilmaley, Co. Clare

The $NFRV_N$ from slurry treatments for both the first and the cumulative harvests were significantly affected by site and month of application. The interaction of site and month of application was significant for the first harvest, but not over cumulative harvests. The predicted mean $NFRV_N$ over all sites, months of application and years for the first harvest was 0.40 and 0.24 kg kg^{-1} for LG, and 0.35 and 0.19 kg kg^{-1} for HG, in April and June, respectively (Figure 1b). The predicted mean $NFRV_N$ over cumulative harvests was 0.37 and 0.23 kg kg^{-1} for LG, and 0.34 and 0.20 kg kg^{-1} for HG, in April and June respectively (Figure 4.1b).

Although the predicted mean $NFRV_N$ was lower for the HG slurry treatment, the difference was not significant for either the first ($P = 0.090$) or cumulative ($P = 0.306$) harvests.

The $NFRV_{DM}$ from slurry treatments for both the first and the cumulative harvests was significantly affected by month of application and grass height. The overall effect of site was significant for the first harvest, but not over cumulative harvests, with the MP site being the highest. The interaction of month of application and site was not significant. The predicted mean $NFRV_{DM}$ over all sites, months of application and years for the first harvest was 0.30 and 0.22 kg kg^{-1} for LG, and 0.20 and 0.11 kg kg^{-1} for HG, in April and June, respectively (Figure 4.1c). The predicted mean $NFRV_{DM}$ over cumulative harvests was 0.38 and 0.23 kg kg^{-1} for LG, and 0.27 and 0.12 kg kg^{-1} for HG, in April and June respectively (Figure 1c). The predicted mean decrease in $NFRV_{DM}$ was 0.11 kg kg^{-1} for HG, as compared to LG, for the first harvest ($P < 0.001$), and 0.10 kg kg^{-1} over cumulative harvests ($P = 0.006$).

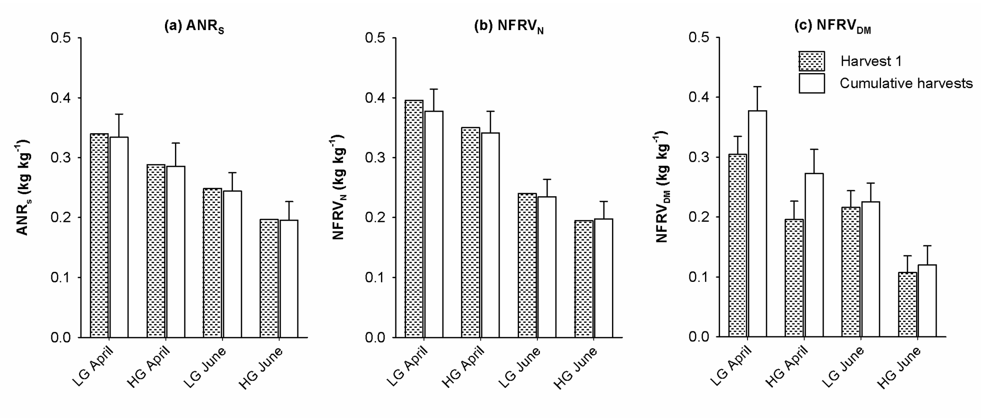

Figure 4.1. Mean apparent recovery of total slurry N applied (ANR_S) (a), mean N replacement fertiliser value based on N uptake ($NFRV_N$) (b), and mean N fertiliser replacement value based on DM yield ($NFRV_{DM}$) (c), for the first harvest following treatment application and cumulative harvests following application for each combination of grass height and month of application over all sites and years. (Error bars indicate SEM).

4.3.4. Soil moisture deficit and grass height

There was no significant interaction of the changes in SMD and grass height on the differences (either ANR_S ($P = 0.964$), $NFRV_N$ ($P = 0.696$) or $NFRV_{DM}$ ($P = 0.153$)) between HG and LG treatments at the first harvest for corresponding year, site and month of application combinations. The SMD at the time of treatment application ranged from -0.7 to 65.5 mm. The lowest ANR_S, $NFRV_N$ and $NFRV_{DM}$

corresponded with the lowest SMD (HG treatment at site JC in June 2007). There was a trend of decreasing ANR_s, $NFRV_N$ and $NFRV_{DM}$ with increasing soil wetness (i.e. a negative change in SMD) between the HG and LG treatments. However, this effect was not significant for ANR_s (P = 0.151), $NFRV_N$ (P = 0.187) or $NFRV_{DM}$ (P = 0.190). The effects of the change in grass height on the change in ANR_S, $NFRV_N$ and $NFRV_{DM}$ at the first harvest for the corresponding year, site and application timing combinations are shown in Figure 4.2. The mean change in grass height had a significant effect on the mean change in ANR_s (P = 0.004; R_2 = 0.63) and $NFRV_N$ (P = 0.012; R_2 = 0.53) (Figure 4.2a and b). The predicted decreases in ANR_s and $NFRV_N$ were 0.056 and 0.052 kg kg^{-1}, respectively, for each 1 cm increase in grass height between LG and HG. The effect of grass height differences on $NFRV_{DM}$ was less significant (P = 0.059; R_2 = 0.34) (Figure 4.2c). The predicted decrease in $NFRV_{DM}$ was 0.030 kg kg^{-1} for each 1 cm increase in grass height between LG and HG slurry applications.

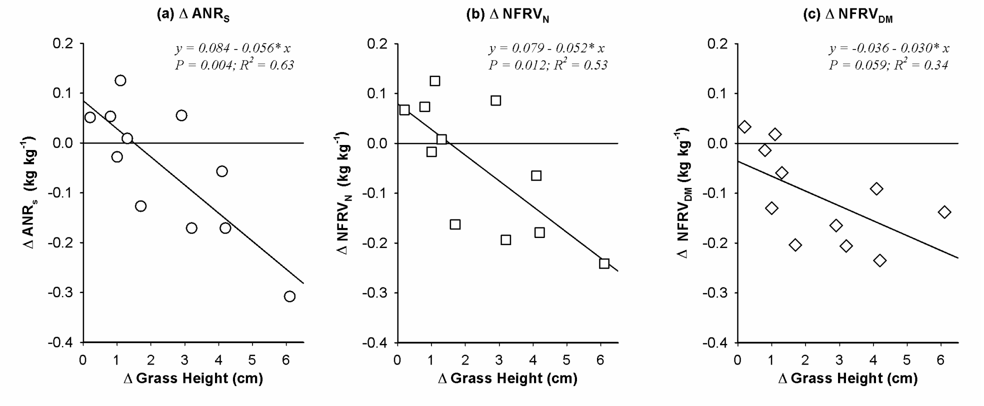

Figure 4.2. Single factor regression models of the effect of the change in grass height between HG and LG treatments (Δ Grass Height (cm)) on the changes in the mean apparent recovery of total slurry N applied (Δ ANR_S) (a), the mean N fertiliser replacement value based on N uptake (Δ $NFRV_N$) (b), and the change in the mean N fertiliser replacement value based on DM yield (Δ $NFRV_{DM}$) (c), for the first harvest following slurry application for corresponding year, site, and month of application combinations.

4.4. Discussion

Delaying the slurry application by between 7 and 19 days and applying slurry into taller grass swards (HG) had significant effects in terms of reducing the DM yield, N uptake, ANR_S and $NFRV_{DM}$ for the first harvest following slurry application, as compared with earlier slurry application to a grass sward freshly cut to a height of 4-5 cm (LG). Whilst the ANR_S, $NFRV_N$, and $NFRV_{DM}$ varied with month of application and site, the decrease with HG compared to LG remained consistent across sites and timings. The ANR_S, $NFRV_N$, and $NFRV_{DM}$ with the HG treatment were 0.05, 0.05 and 0.11 kg kg^{-1} lower, respectively, than with LG for the first harvest. Over cumulative harvests, the ANR_S, $NFNV_N$, and $NFRV_{DM}$ were also decreased with HG compared with LG treatments. However, the effect was only significant for $NFRV_{DM}$, for which the reduction was 0.10 kg kg^{-1}. The lack of a significant difference in ANR_S over cumulative harvests indicates higher residual N effects with HG, compared with LG, in later cuts. This may be partly explained by the reduced growth period between slurry application and the first harvest with the HG treatment compared with the LG treatment. Therefore, slurry N not taken up by the grass in the first harvest period may have been taken up in subsequent harvest period(s). However, the consistent and significant reduction in $NFRV_{DM}$ between treatments over both the first and cumulative harvests indicates that this residual N uptake may be low.

Low ammonia emission slurry application methods have been shown to increase the NFRV of slurry application relative to that of broadcast application using the splash-plate method (Schils and Kok, 2003; Bittman *et al.*, 2005; Schröder *et al.*, 2007; Lalor *et al.*, 2011). This increase in NFRV is commonly attributed to decreased ammonia losses following application (Webb *et al.*, 2010a). The decreases in ANR_S, $NFRV_N$, and $NFRV_{DM}$ for the HG treatment was contrary to results that might have been expected on the basis of previous studies showing reductions in NH_3 emissions following application under taller grass and crop canopies (Sommer and Olesen, 2000; Misselbrook *et al.*, 2002). Thorman *et al.* (2008) developed an algorithm for use in combination with the ALFAM model (Søgaard *et al.*, 2002) that predicted an increase in the ammonia emission-reduction efficiency of surface-banding application methods of 5% per cm increase in grass sward height. The predicted reduction in ammonia emissions due to higher grass heights would have been expected to increase the ANR_S, $NFRV_N$, and $NFRV_{DM}$ for HG compared to LG in this experiment. However, the reverse was found to be the case in our study.

One possible explanation for the decrease in ANR_S, $NFRV_N$, and $NFRV_{DM}$ for the HG treatment in this experiment is the delay in slurry N application with the HG treatment. The delayed application may have resulted in the growth of the grass being restricted on the HG treatment plots prior to the delayed slurry application. This may have reduced the N uptake and subsequent capacity for accumulation of dry matter with the HG slurry treatment compared with the LG treatment, which had slurry applied earlier and had a longer growth period after application. Additionally, the reduced time period between slurry application and harvest may have reduced the time during which the N taken up by the grass plants could have been assimilated into herbage DM. The increase in N concentration in herbage from the

HG treatment compared with LG, might indicate that although the N had been taken up by the grass, the time delay restricted the extent of conversion of the N taken up into additional DM yield. However, while the increased N concentration in herbage with HG compared to LG was significant, the magnitude of the difference was not large enough to avoid the HG treatment having lower total N uptake. The consistency in the values of ANR_S and $NFRV_N$ for the first and cumulative harvests for both LG and HG treatments indicates that N uptake being delayed from the first harvest period to subsequent periods was not a factor explaining the decreases that were obtained for the HG treatment. Large residual differences may also be unlikely, since a significant proportion of ammoniacal-N in slurry applied that is not taken up by plants is immobilised in the soil after application and is subsequently released at a relatively slow rate (Morvan *et al.*, 1997; Sorenson and Amato, 2002; Hoekstra *et al.*, 2011). In an adjacent experiment with matching treatments at the JC site in 2007 and 2008, Hoekstra *et al.* (2010a) found that the recovery of ^{15}N-labelled ammonium-N from slurry was increased by the later application in taller grass; this effect occurred at the first harvest and over cumulative harvests. Therefore, the delay in N application does not explain the decreases that occurred for the HG treatment in our study.

Another explanation for the decrease that occurred for the HG treatment is the effect of the machinery traffic in the taller grass canopy. Frost (1988) measured grass yields in wheel-track areas as low as 0.73 times that of non-tracked areas. However, the effect of wheel traffic was not always significant, and it had its greatest impact on herbage yield in the first harvest period after machinery traffic. Douglas and Crawford (1998) measured a reduction in ANR of slurry from 0.71 kg kg^{-1} (with no compaction) to 0.53 kg kg^{-1} (after compaction). These and other studies associate the occurrence of negative effects on grass yield and N uptake with soil compaction and structural damage, and identify soil wetness as a key indicator of potential soil damage. However, the effect of SMD on the differences in ANR_S, $NFRV_N$, and $NFRV_{DM}$ was not significant in this study. There are few studies of the effects of herbage cover at the time of traffic in relation to the impact of traffic on subsequent grass yield and N uptake. In a study of the effects of tractor wheel traffic in grass silage swards, Frame and Merrilees (1996) highlight the potential direct damage to sward plants and tissues, and concluded that delays between wheel passes of machinery operations following silage harvest should be minimised. The effect of wheel traffic was not directly measured by comparing tracked with non-tracked areas within plots in this study. However, the effect of increasing grass height on reducing the ANR_S, $NFRV_N$, and $NFRV_{DM}$ between the HG and LG treatments may have been due to increased impact of damage, and consequent slower recovery after traffic, of the taller grass swards of the HG treatment compared to the shorter grass swards of the LG treatment application.

Although not objectively quantified in the experiment, variations in sward cover across the plots were evident in some cases at harvest time, with apparent reductions in sward height and density in the areas that had received wheel traffic, compared with the remainder of the plot. Approximately 20% of the width of the plots in this study received wheel traffic. The adjacent study by Hoekstra et al. (2010a), which was conducted on smaller plots that did not receive any wheel tracks, found that the recovery of ^{15}N-labelled ammoniacal N from slurry was increased by the later application in taller grass. Further work is required to identify threshold grass heights that permit traffic for slurry application without restricting yield and N uptake efficiency. Research examining if these negative effects can be overcome by operating machinery that has a wider boom width would also be beneficial, since low ammonia emission application machinery with boom widths up to and above 24 m are commercially available.

The differences in ANR_S, $NFRV_N$, and $NFRV_{DM}$ between LG and HG treatments may also be the result of the experimental design of the experiment, whereby the performance of the slurry treatments was linked to the performance of the fertiliser-N treatments. In the case of the LG treatment, the slurry was applied close to the timing of the N fertiliser. The performance the HG treatment was also compared to the same fertiliser N application and not to a separate set of mineral N fertiliser treatments that could have been applied at the same time as the HG treatment. Such a separate set of mineral N fertiliser treatments that would have corresponded specifically to the HG slurry treatments may have better elucidated the extent that wheel damage alone and the timely availability of N were the major causes of yield reductions that occurred on the HG treatment. However, the approach taken in this experiment was designed to reflect the type of decision that a farmer would have to take in practice. This experiment was designed to represent a situation in which a farmer is restricted from applying slurry, because of unfavourable weather or soil trafficability conditions, at the time that would otherwise have been ideal for fertiliser N and slurry to be applied. The farmer must then base mineral N fertiliser rate decisions on the likely NFRV that might arise from delayed slurry application into a taller grass sward in expectation of improved weather and soil conditions in subsequent days or weeks.

Lalor and Schulte (2008) (Chapter 2 of this thesis) identified that facilitating slurry application into taller grass swards is a key advantage of low emission slurry application methods. Application of slurry in taller swards can assist in overcoming soil trafficability restrictions and increase the window of opportunity for application in spring when the NFRV can be maximised. It has also been shown that the increased costs of trailing shoe relative to broadcast application methods require that additive NFRV increases of both application method and timing of application in weather conditions that reduce NH_3 volatilisation are required in order to offset increased costs of low-emission application methods (Lalor and Schulte, 2008; Lalor *et al.*, 2011). However, the results of this study question the benefits of delaying slurry application in taller swards in order to overcome soil trafficability restrictions. Although application in taller swards may afford greater opportunity for matching application timing with weather conditions that minimise NH_3 losses, the decrease in NFRV due to damage from wheel tracks may counteract the increased NFRV benefits of timing. In this study, both the mean ANR_S and $NFRV_N$ for the first and cumulative harvests, and the mean $NFRV_{DM}$ for the cumulative harvests were higher for HG in April than LG in June (Figure 4.1). Therefore, positive benefits from application in April rather than in June could overcome the negative effect where the application in April is only possible if applied in a taller herbage canopy. The mean ANR_S and $NFRV_N$ and $NFRV_{DM}$ with the trailing shoe method in HG in this study were similar when compared within month of application to that with splash-plate application in the study of Lalor *et al.* (2011) (Chapter 3). Therefore, the use of the trailing shoe method in April in HG would still offer benefits in terms of mineral N fertiliser savings, compared with application in June with the splash-plate method. However, comparisons made within the experiment between sites and months of application are restricted, as the experimental design was unbalanced, with the frequency of treatment applications in June and at the MP and JC sites being higher than those in April, or at the KM site.

The single factor regression models for grass height (Figure 4.2) indicate that grass height increases of 3.1, 4.6 and 1.8 cm for ANR_S, $NFRN_N$ and $NFRV_{DM}$, respectively, were the threshold differences in grass heights for April application, above which application in June would be more beneficial. These threshold heights were estimated as the increases in grass height that would be required to reduce the ANR_S, $NFRN_N$ and $NFRV_{DM}$ to levels below the respective predicted mean value that would be achieved by applying in June to a low grass sward. However, such grass height thresholds are dependant on the design of the application machinery. One of the key considerations is the proportion of the boom width of the spreader that is affected by wheel tracks. The field efficiency of the application regarding headland turning and idle driving will also be significant in determining the total proportion of herbage damaged by wheel traffic. However, while machines are available with booms substantially wider than the 6 m wide applicator used in this experiment, the machinery size and tyre specification in this experiment were designed to represent what is currently typical on grassland farms in Ireland.

4.5. Conclusions

Delaying slurry application, with use of the trailing shoe method, and applying into taller grass swards had significant effects in terms of decreasing the DM yield, N uptake, ANR_S, $NFRV_N$ and $NFRV_{DM}$ following slurry application, as compared with earlier application to a grass sward freshly cut to a height of 4-5 cm. These decreases were significantly affected by the change in grass height between application timings, associated with wheel track damage affecting subsequent N uptake and growth of the taller grass sward. While slurry application in taller swards applied with the trailing shoe method may afford greater opportunity for matching application timing with weather conditions that minimise NH_3 losses, the potential for sward damage from wheel tracks should also be considered, and may counteract the increased NFRV benefits of timing.

4.6. Acknowledgements

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5

Costs of adoption of low ammonia emission slurry application methods on grassland in Ireland

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Abstract

This analysis was conducted to evaluate the economic implications of adopting the low-emission application methods in Ireland, including both the costs and benefits to the farmer. Application methods included were trailing hose (TH), trailing shoe (TS) and shallow injection (SI). The net additional costs of adopting these application methods over conventional splash-plate application were estimated per unit of slurry volume applied (C_u) and per unit of NH_3-N abated (C_{NH3}) using the methodology described in the Integrated Pollution Prevention and Control (IPPC) Best Available Techniques Reference (BREF) document. The C_u increased progressively from TH (€0.59 m^{-3}) to TS (€1.23 m^{-3}) to SI (€1.91 m^{-3}). The C_{NH3} was also lowest with TH (€2.00 kg^{-1}), but was higher with TH (€3.55 kg^{-1}) than with SI (€2.76 kg^{-1}). The benefit of mineral N fertiliser savings due to NH_3-N emission abatement offset 38%, 25% and 20% of the total additional unit costs of TH, TS and SI adoption, respectively. However, the savings were not sufficient to offset the total cost of adoption of any of the techniques. Sensitivity analysis showed that the factors that had greatest impact on the cost were the assumed NH_3-N abatement potentials of each method, the volume of slurry being applied annually with each machine, and the hourly work rate of the equipment. The capital costs of increased tractor power contributed significantly to the total capital cost of adoption of low-emission equipment.

Introduction

The emphasis on maximising the nitrogen fertiliser replacement value (NFRV) of cattle slurry has been revived in Ireland in recent years for a number of reasons. Nitrogen (N) fertiliser prices have increased substantially in recent years, resulting in farmers seeking to make better use of N resources in slurry to offset N fertiliser inputs. This has coincided with the introduction of legislative restrictions in 2006, and updated in 2010, to comply with the EU Nitrates and Water Framework Directives that control the quantities of fertilisers that can be applied to crops. This legislation also specifies the NFRV that must be assumed for cattle slurry applications (Anon, 2010). There has also been a continued emphasis on reducing national ammonia (NH_3) emissions. Approximately 30% of NH_3 emissions from Irish agriculture is attributable to landspreading of cattle slurry (Hyde *et al.*, 2003). While Ireland is currently compliant with current NH_3 emission targets, the requirement to comply with future targets for reduced NH_3 emissions may affect future slurry management practices. The combination of these factors has resulted in farmers becoming more aware of the fertiliser benefits of cattle slurry and improving the NFRV is seen as a key driver of both improving nutrient use efficiency, and decreasing the contribution of landspreading to national NH_3 emissions.

Slurry application method, and in particular its effect on slurry placement, is considered a key determinant of the NFRV of slurry (Schröder, 2005a). Application methods that reduce gaseous losses of N as NH_3 have the potential to increase the NFRV of slurry, since the N not lost to the atmosphere is retained in the soil and may be utilised by the crop. The trailing shoe (TS) application method increased the NFRV of cattle slurry by 0.1 kg kg^{-1} total slurry N applied compared to conventional splash-plate or broadcast (SP) application in grassland experiments in Ireland (Lalor *et al.*, 2011) (Chapter 3 of this thesis).

At present in Ireland, almost all (97%) of the cattle slurry application to grassland is performed using the SP method (Hennessy *et al.*, 2011a). Historically, the most common timing of slurry application was after grass silage harvest in the summer period in the months May to July (Hyde and Carton, 2005). However, in recent years, the proportion of slurry applied in the spring period from mid January to April has increased from 34% in 2003 (Hyde *et al.*, 2006) to 52% in 2009 (Hennessy *et al.*, 2011a) as farmers seek to maximise NFRV by applying slurry in cooler weather conditions.

The environmental benefits of low-emission slurry application methods such as band spreading (using trailing hose (TH) or TS) and injection for reducing the gaseous emissions of NH_3 from landspreading of animal slurries are well established. However, the implementation of these technologies is often limited by the increased purchase and running costs associated with this machinery compared with the SP application method. In some European countries, this obstacle to technology adoption has been overcome by enforcing legislation. Since such legislation is not in place in Ireland, high rates of adoption will be dependant on measurable economic advantages to individual farmers.

5.1.1. Potential for low-emission application methods in Ireland

The TH, TS and shallow injection (SI) methods are the most common low-emission application methods available to grassland farmers. The reductions in NH_3 emissions associated with low-emission application methods compared to SP have been shown to vary between a number of experiments reported. Within the review by Webb *et al.* (2010a), the mean emission abatement from slurry applied to grassland, calculated as the mean % reductions in emissions compared to SP across a range of studies, were 35%, 64% and 80% with TH, TS and SI, respectively. However, the range around these mean values was high. Studies from the UK have shown abatement levels lower than these mean values. Smith *et al*. (2000) measured reductions of 39, 43 and 57%, and Misselbrook *et al*. (2002) measured reductions of 26, 57 and 73% compared to SP for the three methods, respectively. Experiments conducted in Ireland measured a mean reduction in emissions of 36% with TS compared with SP (Dowling *et al.*, in press). Current guidelines in the Integrated Pollution Prevention and Control (IPPC) Best Available Techniques Reference (BREF) document for intensive rearing of poultry and pigs suggests emission reductions compared to SP of 30, 40%, and 60% for TH, TS and SI (open slot) for pig slurry application to grassland (Anon, 2003). This potential range in emission abatement needs to be considered when calculating costs and benefits of low-emission application methods.

The objective of this analysis was to evaluate the economic implications of adopting the low-emission application methods in Ireland, including both the costs and benefits to the farmer. Costs were calculated as the net additional costs of adopting low-emission application methods per unit of slurry volume applied and per unit of NH_3-N abated. The analysis also examined the sensitivity of the calculated costs to variation in a range of input variables such as potential abatement levels achievable, and costs of various inputs that contribute to the net cost of low-emission application method adoption.

5.2. Methodology

5.2.1. Estimating costs

The analysis was conducted following the approach outlined for calculating cost associated with the application of emissions reduction techniques in the BREF document (Anon, 2003). This approach estimates the ‘unit’ cost of techniques, which is defined as the “annual increase in costs that a typical farmer will bear as a result of introducing the technique”. The increase in costs in this case means that only the additional costs incurred due to the adoption of the technique should be included. Therefore, in reality, these increased costs are incurred in addition to the current cost of continuing to apply slurry using the current reference method. The following equation was used for calculating the unit cost (Eqn. 5.1):

Eqn. 5.1

$$C_u = \frac{A_C + A_R + A_L + A_F - A_S}{V},$$

where C_u is the unit cost of the technique (€ m^{-3}); A_C is the annualised cost of additional capital (€ y^{-1}); A_R is the annual cost of additional repairs associated with the technique (€ y^{-1}); A_L is the annual additional labour costs (€ y^{-1}); A_F is the annual additional fuel costs (€ y^{-1}); A_S is the annual savings and/or value of production benefits arising as a result of the technique (€ y^{-1}); and V is the total volume of slurry applied using the technique each year (m^3 y^{-1}).

The value of A_C was calculated as the sum of the annual cost of all the capital investment required. Where separate pieces of investment are required, such as in this case where additional tractor power may be required in addition to the new application equipment, the annual cost of each capital investment was calculated and summed to give the total A_C. Therefore, for landspreading equipment where additional tractor power is also required, the A_C was calculated using the equation (Eqn. 5.2):

Eqn. 5.2.

$$A_C = \left(C_t \times \frac{r_t(1+r_t)^{n_t}}{(1+r_t)^{n_t} - 1}\right) + \left(C_e \times \frac{r_e(1+r_e)^{n_e}}{(1+r_e)^{n_e} - 1}\right),$$

where C_t and C_e are the additional capital investment costs of the tractor and application equipment, respectively (€); r_t and r_e are the interest rates (expressed as a decimal of 1) for the tractor and application equipment, respectively; and n_t and n_e are the terms of the investment for the tractor and application equipment, respectively (y). While the interest rate is likely to be equal for both the tractor and the application machinery, the term of investment may vary. The cost of additional tractor power was calculated using the equation (Eqn. 5.3):

Eqn. 5.3. $$C_t = (P_e - P_o).C_p ,$$

where P_o and P_e are the tractor power requirements to operate the reference equipment and the low-emission application equipment, respectively (kWh); and C_p is the capital cost of the tractor per unit increase in power (€ kWh^{-1}).

The value of A_R was calculated on the basis that the additional repair cost can be calculated as a percentage of the additional capital cost, using the equation (Eqn. 5.4):

Eqn. 5.4. $$A_R = C_t.rm_t + C_e.rm_e ,$$

where rm_t and rm_e are the annual repair cost rate of the additional capital cost of the tractor (C_t) and application equipment (C_e), respectively (expressed as a decimal of 1).

A change in labour costs may arise due to the application technique having a different work rate than the reference method. Hence the number of hours work required may change due to increased hours required to apply the same volume of slurry. Labour costs may also change due to the new application machinery requiring a more skilled and highly paid operator. The value of A_L was calculated as the sum of the labour cost for additional hours that may be required to apply the same volume of slurry at a slower work rate, and the additional labour cost associated with paying an operator a higher rate for all hours worked because of the increased operator skill required., using the equation (Eqn. 5.5):

Eqn. 5.5. $$A_L = L_e.(H_e - H_o) + H_o.(L_e - L_o),$$

where L_e and L_o are the hourly labour costs assumed with the low-emission application method and with the reference method, respectively (€ h^{-1}); and H_e and H_o are the hours of labour required each year with the low-emission application method and with the reference method, respectively (h y^{-1}). The values of H_o and H_e can be calculated using the equation (Eqn. 5.6):

Eqn. 5.6. $$H_{o,e} = \frac{V}{R_{o,e}} ,$$

where R_o and R_e are the slurry application rate with the reference equipment and the low-emission application equipment, respectively (m^3 h^{-1}). The value of R_e was estimated by applying a coefficient to the value assumed for R_o to account for changes in spreading work rate based on differences in the bout width of the machine. This approach assumed that the time in the tanker load cycle that was spent filling and travelling between the field and the store was constant with all methods. It was also assumed that the tractor forward speed during the time spent spreading in the field was constant across application methods. Therefore, the difference in work rate between the application methods was assumed to be only affected by the time spent emptying the tanker. The narrower the working width of the machine, the longer it takes to empty the tanker. Therefore, R_e was calculated using the following equation (Eqn. 5.7):

Eqn. 5.7. $$R_e = \frac{R_o}{1 - T_s + \left(T_s \cdot \frac{w_o}{w_e}\right)},$$

where T_s was the proportion of the tanker load cycle time spent applying slurry in the field; W_o was the working width of the reference equipment (m); and W_e was the working width of the low-emission application equipment (m).

Additional fuel costs may be incurred due to the low-emission application for two reasons. Firstly, an increased power requirement of the tractor will result in higher fuel requirements for the hours worked that would have been worked with the reference method. Secondly, additional fuel will be required due to the additional hours due to the decrease in work rate with the low-emission method. The value of A_F was calculated using the following equation (Eqn. 5.8):

Eqn. 5.8. $$A_F = C_f.\left(F_p.H_o.\left(P_e - P_o\right) + F_p.P_e.\left(H_e - H_o\right)\right),$$

where C_f was the cost of fuel (€ L^{-1}); and F_p was the hourly fuel consumption per kWh of tractor power (L h^{-1} kWh^{-1}).

The term A_S was calculated based on the potential for the low-emission application technique to result in mineral N fertiliser cost savings. Other potential benefits of low-emission application methods compared to the reference SP application method could also be argued for inclusion such as the fertiliser benefits of more uniform application, or the reduction of odour emissions or pasture contamination. However, in this study, only the N fertiliser benefit was considered. It was assumed that NH_3-N not volatilised could replace mineral N fertiliser requirements on a 1:1 basis. The value of A_S was calculated using the following equation (Eqn. 5.9):

Eqn. 5.9. $$A_S = N.V.T.\left(\frac{E_o}{100}.\frac{E_e}{100}\right),$$

where N was the cost of mineral-N fertiliser (€ kg^{-1}); T was the total ammoniacal N in slurry (kg m^{-3}); E_o was the NH_3 emission factor for the reference method, expressed as loss of NH_3-N as a percentage of the TAN applied (%); and E_e was the NH_3 emission abatement potential of the low-emission application method (%).

The cost of each technique per kg of NH_3-N emission abated was also calculated using the following equation (Eqn. 5.10):

Eqn. 5.10. $$C_{NH3} = \frac{C_u}{T.\left(\frac{E_o}{100}.\frac{E_e}{100}\right)},$$

where C_{NH3} was the additional cost of adopting the low-emission application method per kg of NH_3-N emission abated (€ kg^{-1}).

5.2.2. Assumptions adopted for comparing costs of application methods

The C_u and C_{NH3} for each of the low-emission application methods of TH, TS and SI were calculated relative to a reference method of SP application. A number of assumptions were made for the parameters in Equations 6.1 to 6.10. The assumed values of these parameters and the rationale for these assumptions are listed in Table 5.1.

Table 5.1. Assumed values of parameters required for cost calculations, and the rationale and justification of each assumption adopted.

Parameter	Unit	Assumed Value				Rationale and justification
		SP*	TH*	TS*	SI*	
V	m^3 y^{-1}	10,000				Assumed as an average annual workload for machine operated by a contractor.
r_t		0.07				Average current interest rate for farm finance.
n_t	y	10				Typical life span of medium to high power tractor.
C_e	€	-	12,000	20,000	25,000	Typical additional prices in Ireland for low-emission application machinery compared with SP tanker of equal size, including additional hydraulic and electrical fittings and chopping systems.
r_e		0.07				Typical interest rate on medium term borrowing for farm machinery.
n_e	y	7				Typical life span of application equipment.
P_o	kWh	75	-	-	-	Typical power requirement for a 9 m^3 SP tanker.
P_e	kWh	-	85	100	120	Progressively higher tractor power requirement is assumed with each low-emission application method due to increased weight and contact with soil.
C_p	€ kWh^{-1}	930				Based on comparison of tractor price listings (Anon, 2012b).
rm_t		0.08				BREF guidelines suggest a value of 5-8% for tractors (Anon, 2003).
rm_e		-	0.10			BREF guidelines suggest a value of 3-6% on slurry spreaders. However, a higher value was assumed in this case due to expected high maintenance due to moving parts and soil contact (Anon, 2003).

* SP = splash-plate (reference method); TH = trailing hose; TS = trailing shoe; and SI = shallow injection. One value is shown where assumptions are equal for all application methods.

Table 5.1.(continued).

Parameter	Unit	Assumed Value				Rationale and justification
		SP*	TH*	TS*	SI*	
L_o	€ h^{-1}	12	-	-	-	Higher labour costs were assumed for the low-emission application methods due to the requirement for more skilled operator due to the increase in machine complexity and value
L_e	€ h^{-1}	-	15	15	15	
R_o	m^3 h^{-1}	30	-	-	-	Typical hourly work rate for a 9 m^3 tanker (3.3 loads per hour).
T_s		0.25	-	-	-	Typical proportion of load spreading cycle that is spent in the field.
W_o	M	10	-	-	-	SP spread width can vary considerably. An average width of 10 m is assumed.
W_e	M	-	6	6	4	Widths assumed are typical of commonly available units suitable for applications to grassland.
C_f	€ L^{-1}	0.90				Typical price of agricultural diesel in Ireland in February 2012.
F_p	L h^{-1} kWh^{-1}	0.30				Fuel requirement per kWh of power is typically in the range 0.25 to 0.35 L kWh^{-1} (Kim *et al.*, 2005).
N	€ kg^{-1}	1.20				Typical price of mineral N fertiliser based on price in Ireland in February 2012.
T	kg m^{-3}	1.8				Typical total N concentration in cattle slurry in Ireland is 3.6 kg m^{-3} (Coulter, 2004). Approximately 50% of the total N is assumed to be present in the form of NH_3-N (DEFRA, 2010).
E_o	%	55	-	-	-	Mean emissions of NH_3-N as a % of TAN following SP application as measured in Irish studies (Dowling *et al.*, in press).
E_e	%	-	30	35	70	Emission abatement efficiencies of 30, 60 and 70 % are assumed for TH, TS and SI, respectively, compared to application with SP in UNECE Guidance document (UNECE, 2007). Respective average emission abatement of 35, 65 and 70 % are reported in the literature (Webb *et al.*, 2010a). Studies in Ireland measured emission reduction of 36% with TS compared with SP (Dowling *et al.*, in press).

* SP = splash-plate (reference method); TH = trailing hose; TS = trailing shoe; and SI = shallow injection. One value is shown where assumptions are equal for all application methods.

5.2.3. Sensitivity analysis

Given that the values assumed for many of the parameters required are based on typical and current estimates of various parameters, a sensitivity analysis was also conducted to examine the influence of changes in these factors over time on the cost estimates of the application machinery. The sensitivity analysis was conducted on a single factor basis by calculating the value of C_u and C_{NH3} by adjusting the value of one parameter while holding all other parameters constant.

The parameters considered for sensitivity analysis were the emission abatement efficiency of the low-emission application method (E_e) in the range of 20 to 90 %; the cost of mineral N fertiliser (N) in the range of €0.70 kg1 to €1.50 kg^{-1}; manure volume (V) in the range of 500 to 20,000 m^3 y^{-1}; the tractor power requirement for the low-emission application equipment (P_e) in the range of 75 to 150 kWh; additional capital cost of the application equipment (C_e) in the range of €5,000 to €40,000; the hourly application rate of the reference SP method (R_o) in the range of 10 to 40 m^3 h^{-1}; interest rate for both tractor and equipment ($r_{t,e}$) in the range of 0.04 to 0.10; the repair cost rate for the tractor and equipment ($rm_{t,e}$) in the range of 0.03 to 0.15; and the cost of fuel (C_f) in the range of €0.50 L^{-1} to €1.20 L^{-1}.

5.3. Results

5.3.1. Costs of application methods

The calculated values of C_u and C_{NH3} for each of the low-emission application methods are shown in Table 5.1. The TH method had the lowest C_u while the SI method had the highest. However, the TS method had a higher C_{NH3} value than the SI method. This was mainly due to the SI method having a higher assumed NH_3 emission abatement potential, and therefore the higher unit cost of SI was offset by a higher level of NH_3 abatement when compared with the TS method.

Table 5.2. Additional units cost (C_u) and cost per kg NH_3 abated (C_{NH3}) with trailing hose (TH), trailing shoe (TS) and shallow injection (SI) compared with the reference application method of splash-plate. Calculations were based on the parameter values assumed in Table 5.1.

Application Method	C_u (€ m^{-3})	C_{NH3} (€ kg^{-1}) NH_3-N abated
TH	€ 0.59	€ 2.00
TS	€ 1.23	€ 3.55
SI	€ 1.91	€ 2.76

The contribution of capital costs (A_c), repairs and maintenance (A_R), labour (A_L), fuel (A_F) and savings (A_S) to the overall value of C_u is shown in Figure 5.1. The total units cost of adoption of the low-emission application equipment were €0.95 m^{-3}, €1.65 m^{-3} and €2.74 m^{-3} for TH, TS and SI, respectively. The differences between the total costs and the C_u of each method were due to savings in mineral N fertiliser due to the reduced NH_3-N emissions compared with the reference method (A_S). These savings offset 38%, 25% and 20% of the total additional unit costs of TH, TS and SI adoption, respectively.

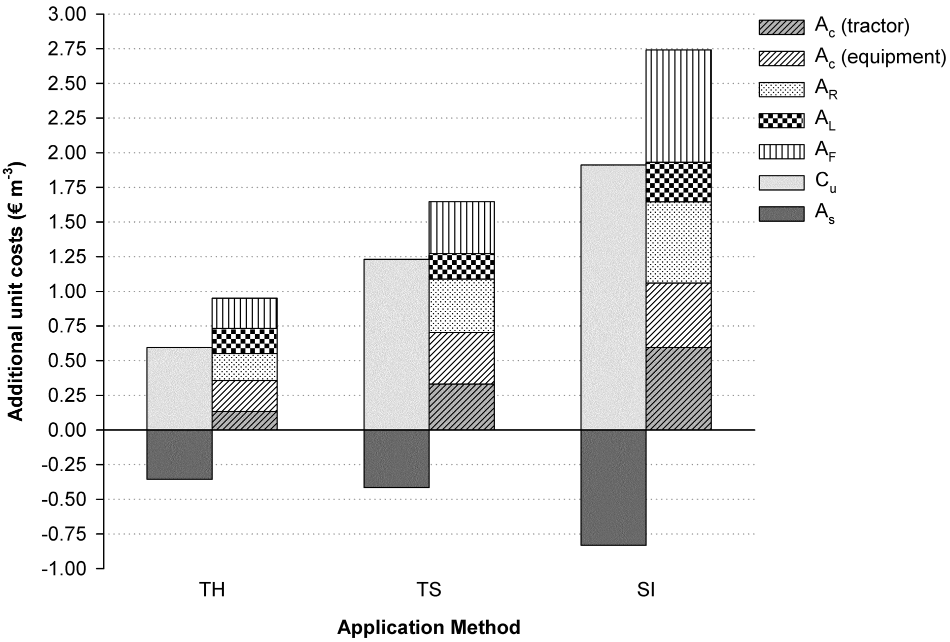

Figure 5.1. Contribution of the additional costs of capital (A_c), repairs and maintenance (A_R), labour (A_L) and fuel (A_F), and the value of savings in mineral N fertiliser (A_S) to the overall unit cost (C_U) of the trailing hose (TH), trailing shoe (TS), and shallow injection (SI) application methods. Capital costs are divided into costs associated with the requirement for additional tractor power (A_c (tractor)) and costs associated with purchasing equipment (A_c (equipment)).

Capital costs (A_c) accounted for the largest percentage of total costs for all methods, being 37%, 43% and 39% for TH, TS and SI, respectively. The percentage of capital costs due to the equipment was higher with TH (63% of A_c) than with TS (53% of A_c), which was higher than SI (44% of A_c).

Repairs and maintenance costs (A_R) accounted for 20%, 23% and 21% of the total costs for TH, TS and SI methods, respectively. Labour costs (A_L) accounted for the smallest proportion of increased costs for all methods, being 19%, 10% and 11% for the TH, TS and SI methods, respectively. Fuel costs (A_F) accounted for 23%, 23% and 30% of the total costs for TH, TS and SI methods, respectively.

5.3.2. Sensitivity analysis

5.3.2.1. Additional unit cost (C_u)

The effects of varying the assumptions of a number of the cost calculation input variables on C_u are shown in Figure 5.2. Across the ranges of all the cost calculation inputs examined, the TH method consistently had the lowest C_u, while SI had the highest. The TS method was intermediate in the case of all variables examined.

The effect of varying the NH_3 abatement potential (E_e) of each application method on C_u is shown in Figure 5.2a. The total range of E_e included in the analysis was 20 to 90%. However, the ranges were restricted within each method to 20 to 60% with TH, 25 to 70% with TS, and 40 to 90% with SI. This distinction between methods was made to reflect reasonable extremes of the E_e of each method based on previous studies (Webb *et al.*, 2010a; Dowling *et al.*, in press). Within the range of E_e included for each method, the C_u ranged from €2.27 m^{-3} to €1.67 m^{-3} with SI, from €1.35 m^{-3} to €0.81 m^{-3} with TS, and from €0.71 m^{-3} to €0.24 m^{-3} with TH. The effect of E_e was linear. A change in E_e of 10% resulted in a change in the C_u of €0.119 m^{-3} with all methods.

The effect of varying the cost of mineral N fertiliser (N) on C_u is shown in Figure 5.2b. The effect of varying N was more significant with the SI method than with the TH method, reflecting the higher fertiliser N savings with SI due to the higher NH_3 emission abatement potential. Within the range of N from €0.70 kg^{-1} to €1.50 kg^{-1} included, the C_u ranged from €2.26 m^{-3} to €1.70 m^{-3} with the SI method, from €1.40 m^{-3} to €1.13 m^{-3} with the TS method, and from €0.74 m^{-3} to €0.50 m^{-3} with the TH method. The effect of N was linear, with a change in N of €0.1 kg^{-1} resulting in an inverse change in C_u of €0.069 m^{-3}, €0.035 m^{-3}, and €0.030 m^{-3} with SI, TS and TH methods, respectively. In order for savings in fertiliser N to fully offset the additional costs of the equipment, (i.e. to achieve a value of C_u of €0.00 m^{-3}) the value of N of €3.96 kg^{-1}, €4.75 kg^{-1} and €3.20 kg^{-1} would be required with SI, TS and TH methods, respectively.

The volume of slurry applied annually with each machine (V) had a large effect on C_u. The range of V with a typical farmer-owned machine is shown in Figure 5.2c. The range of 500 to 2,000 m^3 y^{-1} is approximately equivalent to the slurry produced from a herd of approximately 40 to 150 dairy cows plus followers over a winter period of 18 weeks (Anon, 2010). Within this range of V, the C_u ranged from €33.16 m^{-3} to €8.49 m^{-3} with the SI method, from €21.91 m^{-3} to €5.58 m^{-3} with the TS method, and from €11.03 m^{-3} to €2.79 m^{-3} with the TH method.

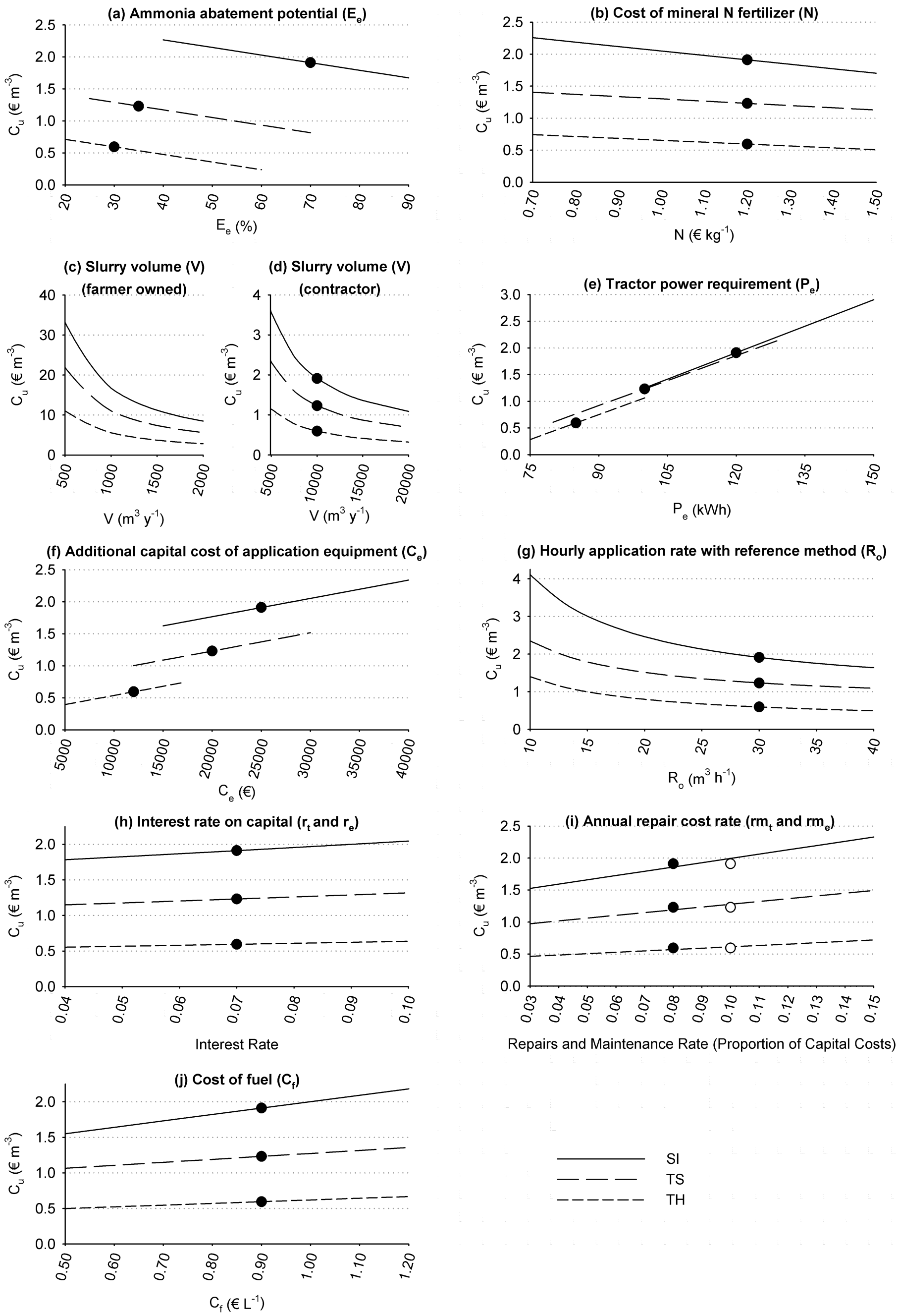

Figure 5.2. Sensitivity of the additional unit cost (C_u) of adopting trailing hose (TH), trailing shoe (TS) and shallow injection (SI) to variation in the values assumed for a number of cost calculation input variables. Solid shaded circles indicate the assumed value and corresponding C_u for each variable. In the case of annual repair cost rate (i), the solid circles indicate assumed value of rm_t and the open circles indicate the assumed values of rm_e.

The range of 5,000 to 20,000 m^3 y^{-1} shown in Figure 5.2d is more typical of the slurry volume applied annually by a contractor. Within this range of V, the C_u ranged from €3.55 $m^{-3}$to €1.09 m^{-3} with the SI method, from €2.32 m^{-3} to €0.69 m^{-3} with the TS method, and from €1.14 m^{-3} to €0.32 m^{-3} with the TH method.

The effect of varying the tractor power requirement (P_e) on C_u is shown in Figure 5.2e. The total range of P_e included in the analysis was 75 to 150 kWh. However, the ranges were restricted within each method to 75 to 100 kWh with TH, 80 to 130 kWh with TS, and 100 to 150 kWh with SI. Within the range of P_e included for each method, the C_u ranged from €1.25 m^{-3} to €2.90 m^{-3} with the SI method, from €0.61 m^{-3} to €2.17 m^{-3} with the TS method, and from €0.28 m^{-3} to €1.06 m^{-3} with the TH method. The effect of P_e was linear, with a change in P_e of 1 kWh resulting in a change in the C_u of approximately €0.031 m^{-3} with all methods.

The effect of varying the cost of application equipment (C_e) on C_u is shown in Figure 5.2f. The total range of costs included in the analysis was €5,000 to €40,000. However, the ranges were restricted within each method to €5,000 to €17,000 with TH, €12,000 to €30,000 with TS, and €15,000 to €40,000 with SI. This distinction between methods was applied in order to reflect reasonable extremes of the C_e of each method for machine working widths assumed. Within the range of C_e included for each method, the C_u ranged from €1.62 m^{-3} to €2.34 m^{-3} with the SI method, from €1.00 m^{-3} to €1.52 m^{-3} with the TS method, and from €0.39 m^{-3} to €0.74 m^{-3} with the TH method. The effect of C_e was linear, with a change in C_e of €1,000 resulting in a change in the C_u of €0.029 m^{-3} with all methods.

The effect of varying the assumption of the hourly application rate with the reference method (R_o) on C_u is shown in Figure 5.2g. The value of R_o has a large effect on C_u, particularly at lower hourly application rates that are typical where slurry has to be transported longer distances between the slurry store and the field. Decreasing the value of R_o from the baseline assumption of 30 m^3 h^{-1} to 10 m^3 h^{-1} increased the C_u to €4.11 m^{-3}, €2.35 m^{-3} and €1.40 m^{-3} with SI, TS and TH, respectively. Increasing the value of R_o to 40 m^3 h^{-1} decreased C_u to €1.64 m^{-3}, €1.09 m^{-3} and €0.49 m^{-3} with SI, TS and TH, respectively.

The effect of varying interest rate (r_t and r_e) on C_u is shown in Figure 5.2h. The effect of varying r_t and r_e was more significant with the SI method than with the TH method, reflecting the higher capital investment costs with SI. Within the range of interest rates from 0.04 to 0.10 included, the C_u ranged from €1.78 m^{-3} to €2.05 m^{-3} with the SI method, from €1.15 m^{-3} to €1.32 m^{-3} with the TS method, and from €0.55 m^{-3} to €0.64 m^{-3} with the TH method. The effect of interest rate was approximately linear, with a change in the interest rate of 0.01 resulting in a change in the C_u of €0.044 m^{-3}, €0.028 m^{-3}, and €0.014 m^{-3} with SI, TS and TH methods, respectively.

The effect of varying the repairs and maintenance rate (rm_t and rm_e) on C_u is shown in Figure 5.2i. The effect of varying rm_t and rm_e was more significant with the SI method than with the TH method, reflecting the higher capital investment costs with SI. Within the range of rm_t and rm_e from 0.03 to 0.15 included, the C_u ranged from €1.53 m^{-3} to €2.33 m^{-3} with the SI method, from €0.97 m^{-3} to €1.49 m^{-3} with the TS method, and from €0.46 m^{-3} to €0.72 m^{-3} with the TH method. The effect of repairs and maintenance rate was linear, with a change in the repairs and maintenance rate of 0.01 resulting in a change in C_u of €0.067 m^{-3}, €0.043 m^{-3}, and €0.040 m^{-3} with SI, TS and TH methods, respectively.

The effect of varying the cost of fuel (C_f) on C_u is shown in Figure 5.2j. The effect of varying C_f was more significant with the SI method than with the TH method, reflecting the higher fuel requirements of this method due to higher power requirement and reduced work rate. Within the range of C_f from €0.50 L^{-1} to €1.20 L^{-1} included, the C_u ranged from €1.55 m^{-3} to €2.18 m^{-3} with the SI method, from €1.06 m^{-3} to €1.36 m^{-3} with the TS method, and from €0.50 m^{-3} to €0.67 m^{-3} with the TH method. The effect of C_f was linear, with a change in C_f of €0.1 L^{-1} resulting in a change in C_u of €0.090 m^{-3}, €0.042 m^{-3}, and €0.024 m^{-3} with SI, TS and TH methods, respectively.

5.3.2.2. Additional unit cost per kg of NH_3-N abated

The effect of varying a number of the assumptions on C_{NH3} is shown in Figure 5.3. In contrast with C_u where the SI method had consistently higher costs, the TS method C_{NH3} is the highest cost method, and is most sensitive to variation in the cost calculation variables.

The only variable that showed exception to this trend was the NH_3 abatement potential (E_e), where the SI resulted in the highest C_{NH3} of all machines at equal levels of E_e (Figure 5.3a). Within the range of E_e included for each method, the C_{NH3} ranged from €5.72 kg^{-1} to €1.88 kg^{-1} with SI, from €5.45 kg^{-1} to €1.18 kg^{-1} with TS, and from €3.60 kg^{-1} to €0.40 kg^{-1} with TH. Unlike with C_u, the effect of E_e on C_{NH3} was not linear, with the sensitivity to change increasing with decreasing values of E_e.

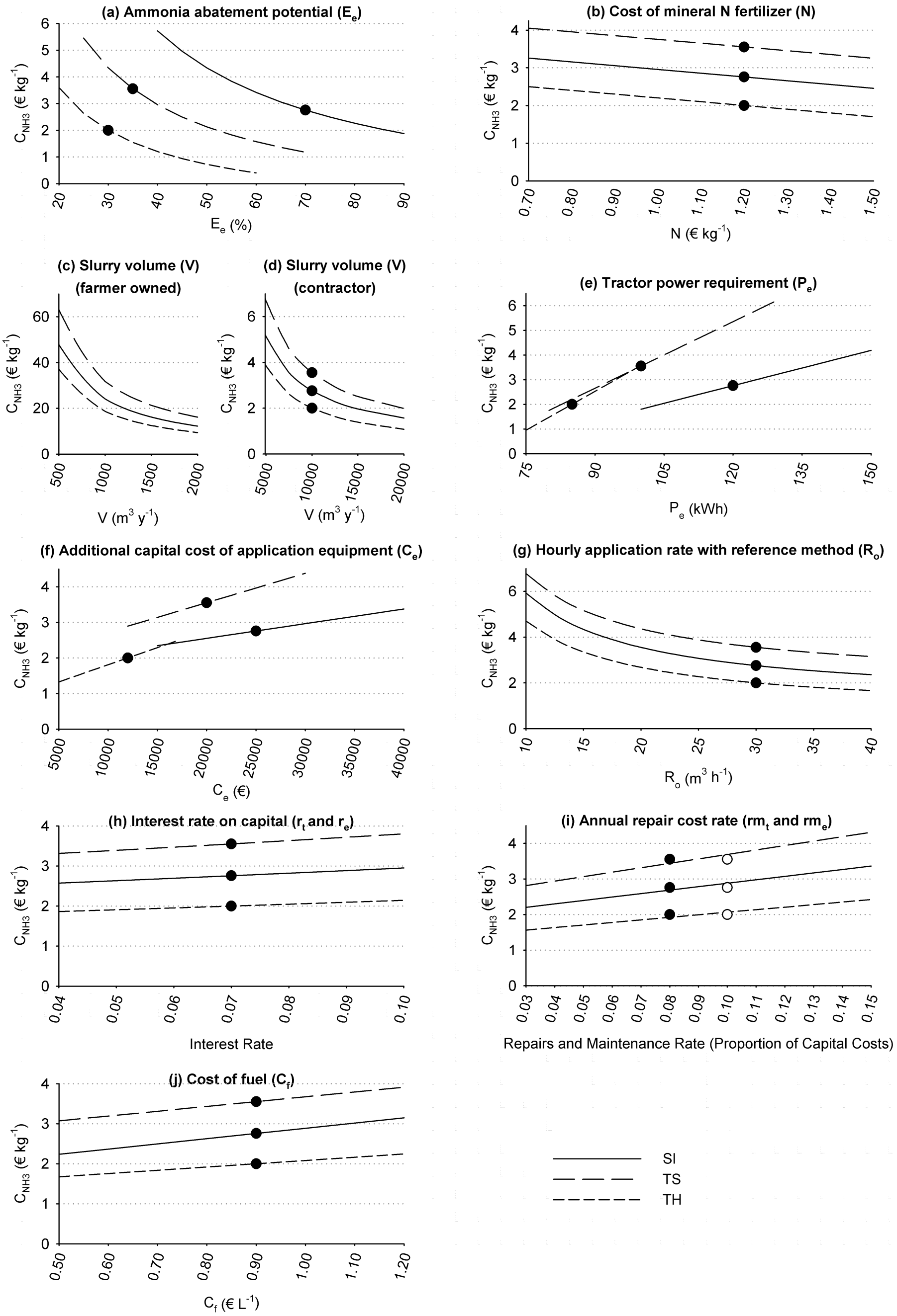

Figure 5.3. Sensitivity of the additional unit cost per kg NH_3-N abated (C_{NH3}) of adopting trailing hose (TH), trailing shoe (TS) and shallow injection (SI), to variation in the values assumed for a number of cost calculation input variables. Solid shaded circles indicate the assumed value and corresponding C_{NH3} for each variable. In the case of annual repair cost rate (i), the solid circles indicate assumed value of rm_t and the open circles indicate the assumed values of rm_e.

The effect of varying the cost of mineral N fertiliser (*N*) on C_{NH3} is shown in Figure 5.3b. The effect of varying *N* was similar with all methods since the NH_3-N abated by each method corresponds to fertiliser N savings. Within the range of *N* from €0.70 kg^{-1} to €1.50 kg^{-1} included, the C_{NH3} ranged from €4.05 kg^{-1} to €3.25 kg^{-1} with the TS method, from €3.26 kg^{-1} to €2.46 kg^{-1} with the SI method, and from €2.50 kg^{-1} to €1.70 kg^{-1} with the TH method. The effect of *N* was linear, with a change in *N* of €0.1 kg^{-1} resulting in an inverse change in C_{NH3} of €0.1 kg^{-1} with all methods.

The volume of slurry applied annually with each machine (*V*) had a large effect on C_{NH3}. The range of *V* with a typical farmer-owned machine is shown in Figure 5.3c. Within this range of *V*, the C_{NH3} ranged from €63.22 kg^{-1} to €16.11 kg^{-1} with the TS method, from €47.84 kg^{-1} to €12.25 kg^{-1} with the SI method, and from €37.15 kg^{-1} to €9.40 kg^{-1} with the TH method. Within the range of 5,000 to 20,000 m^3 y^{-1} more typical to a contractor (Figure 5.3d), the C_{NH3} ranged from €6.69 kg^{-1} to €1.98 kg^{-1} with the TS method, from €5.13 kg^{-1} to €1.57 kg^{-1} with the SI method, and from €3.85 kg^{-1} to €1.07 kg^{-1} with the TH method.

The effect of varying the tractor power requirement (P_e) on C_{NH3} is shown in Figure 5.3e. The C_{NH3} was more sensitive to a changes in P_e in the case of the TH and TS methods compared to SI, since with SI, the increased cost associated with higher power were offset to a greater extent by fertiliser N saved due to the higher assumption of E_e. Within the range of P_e included for each method, the C_{NH3} ranged from €1.75 kg^{-1} to €6.25 kg^{-1} with the TS method, from €1.80 kg^{-1} to €4.19 kg^{-1} with the SI method, and from €0.95 kg^{-1} to €3.57 kg^{-1} with the TH method. The effect of P_e was linear, with a change in P_e of 1 kWh resulting in a change in the C_{NH3} of €0.090 kg^{-1}, €0.048 kg^{-1} and €0.105 kg^{-1} with TS, SI and TH methods, respectively.

The effect of varying the cost of application equipment (C_e) on C_{NH3} is shown in Figure 5.3f. Within the range of C_e included for each method, the C_{NH3} ranged from €2.89 kg^{-1} to €4.38 kg^{-1} with the TS method, from €2.34 kg^{-1} to €3.37 kg^{-1} with the SI method, and from €1.33 kg^{-1} to €2.48 kg^{-1} with the TH method. The effect of C_e was linear, with a change in C_e of €1,000 resulting in a change in the C_{NH3} of €0.082 kg^{-1}, €0.041 kg^{-1} and €0.096 kg^{-1} with TS, SI and TH methods, respectively.

The effect of varying the assumption of the hourly application rate with the reference method (R_o) on C_{NH3} is shown in Figure 5.3g. The value of R_o has a large effect on C_{NH3}, particularly at lower hourly application rates. Decreasing the value of R_o from the baseline assumption of 30 m^3 h^{-1} to 10 m^3 h^{-1} increased the C_{NH3} to €6.77 kg^{-1}, €5.92 kg^{-1} and €4.70 kg^{-1} with TS, SI and TH, respectively. Increasing the value of R_o to 40 m^3 h^{-1} decreased C_{NH3} to €3.15 kg^{-1}, €2.36 kg^{-1} and €1.66 kg^{-1} with TS, SI and TH, respectively.

The effect of varying interest rate (r_t and r_e) on C_{NH3} is shown in Figure 5.3h. Within the range of interest rates from 0.04 to 0.10 included, the C_{NH3} ranged from €3.31 kg^{-1} to €3.80 kg^{-1} with the TS method, from €2.57 kg^{-1} to €2.95 kg^{-1} with the SI method, and from €1.86 kg^{-1} to €2.14 kg^{-1} with the TH method. The effect of interest rate was approximately linear, with a change in the interest rate of 0.01 resulting in a change in the C_{NH3} of €0.081 kg^{-1}, €0.063 kg^{-1}, and €0.047 kg^{-1} with TS, SI and TH methods, respectively.

The effect of varying the repairs and maintenance rate (rm_t and rm_e) on C_{NH3} is shown in Figure 5.3i. Within the range of rm_t and rm_e from 0.03 to 0.15 included, the C_{NH3} ranged from €2.81 kg^{-1} to €4.31 kg^{-1} with the TS method, from €2.20 kg^{-1} to €3.36 kg^{-1} with the SI method, and from €1.56 kg^{-1} to €2.42 kg^{-1} with the TH method. The effect of repairs and maintenance rate was linear, with a change in the repairs and maintenance rate of 0.01 resulting in a change in C_{NH3} of €0.125 kg^{-1}, €0.096 kg^{-1}, and €0.072 kg^{-1} with TS, SI and TH methods, respectively.

The effect of varying the cost of fuel (C_f) on C_{NH3} is shown in Figure 5.3j. Within the range of C_f from €0.50 L^{-1} to €1.20 L^{-1} included, the C_{NH3} ranged from €3.07 kg^{-1} to €3.91 kg^{-1} with the TS method, from €2.24 kg^{-1} to €3.15 kg^{-1} with the SI method, and from €1.67 kg^{-1} to €2.24 kg^{-1} with the TH method. The effect of C_f was linear, with a change in C_f of €0.1 L^{-1} resulting in a change in C_{NH3} of €0.121 kg^{-1}, €0.130 kg^{-1}, and €0.081 kg^{-1} with TS, SI and TH methods, respectively.

5.4. Discussion

The methodology adopted in this study only calculates additional unit costs. However, to calculate total slurry application costs with the low-emission methods, an estimate of the cost with the reference method (splash-plate) is required. Contractors typically charge for slurry application on an hourly basis. Charges quoted for slurry application with splash-plate are typically in the range of €50-55 h^{-1} (Anon, 2008), although considerable variation between specific farms and contractors can be expected. Assuming an application rate of 30 m^3 h^1, this equates to a cost of €1.67 to €1.83 m^{-3}. Lalor (2008) estimated the cost of splash-plate application to be €1.55 m^{-3}. Based on this range of costs for splash-plate application, the adoption of TH, TS or SI would increase slurry application costs by approximately 32-38% to €2.14 m^{-3} - €2.42 m^{-3} with TH, by 67-79% to €2.78 m^{-3} - €3.06 m^{-3} with TS, or by 104-123% to €3.46 m^{-3} - €3.74 m^{-3} with SI. Assuming the use of contractors for slurry application, the increased costs of adoption of these techniques would represent an increase in direct costs on farms of approximately 1 to 4% based on data of costs on dairy and cattle farms from the National Farm Survey of 2010 (Hennessy *et al.*, 2011b).

These additional and total cost estimates fall within published ranges of costs of slurry application with low-emission application equipment. Huijsmans *et al.*, (2004) estimated that average costs of manure application on grassland were €2.82 m^{-3}, €3.75 m^{-3}, €3.92 m^{-3}, and €4.64 m^{-3} with SP, TH, TS and SI, respectively, for annual slurry application rates of 3000 m^3 y^{-1}. The same study also reported a range of manure application costs from €1.65 m^{-3} to €13.02 m^{-3} for farms in a range of countries. However, in many cases, the slurry volume applied annually was relatively low (<5,000 m^3) compared with the annual application of 10,000 m^3 assumed in this study. Döhler *et al.* (2011) estimated slurry application costs with splash-plate in the range of €2.49 m^{-3} to €6.61 m^{-3} across a range of annual slurry application rates. At an annual application rate of to 10,000 m^3, equal to that assumed in this study, the cost of splash-plate was €3.04 m^{-3}. The additional costs of adoption of TH, TS and SI were estimated to be €0.34 m^{-3}, €1.07 m^{-3} and €1.33 m^{-3}, respectively. The additional costs per kg of NH_3-N emission abated were estimated to be €1.14 kg^{-1}, €1.77 kg^{-1} and €1.47 kg^{-1} with TH, TS and SI, respectively. While these estimates of increased costs per unit volume of slurry and per kg of NH_3-N emission abated are lower than those estimated in this study, the ranking of the three techniques based on costs is consistent with the estimates of Döhler *et al.* (2011).

The TH application method had the lowest additional costs both in terms of C_u and C_{NH3}. However, the method with the highest costs depended on the metric used for comparison of the TS and SI methods. The high C_{NH3} of TS was partly due to the low value of E_e (35%) assumed in this analysis. While this assumed level of abatement is consistent with the findings of Irish research (Dowling *et al.*, in press), it is lower than higher values of up to 60-65% that might be assumed based on other data sources (Anon, 2003; Webb *et al.*, 2010a). The sensitivity analysis showed that the C_u (Figure 5.2a) and C_{NH3} (Figure 5.3a) would have been reduced to €0.93 m^{-3} and €1.57 kg^{-1}, respectively, if a value of E_e of 60% had been assumed for TS. In this scenario, the TS would have been the lowest cost option based on C_{NH3}. However, the assumption of the lower value of E_e for TS in an Irish context is justified based on data from Irish studies (Dowling *et al.*, in press).

The estimated additional unit costs are highly dependent on the assumptions used for the range of factors that contribute to costs. Of the factors that were isolated in the sensitivity analysis, C_u was most sensitive to changes in V and R_o, while C_{NH3} was also highly sensitive to changes in E_e. In the case of V, applying higher volumes of slurry has the effect of spreading the total costs of application over a larger volume of slurry, and over a larger quantity of NH_3-N emission abatement.

For slurry volumes typical of farmer owned machines (Figure 5.2c and Figure 5.3c), both the C_u and C_{NH3} are increased by factors of between approximately 4 and 18 with all three low-emission methods compared with the baseline scenario assumption of V of 10,000 $m^3\ y^{-1}$. Approximately 50% of slurry in Ireland is applied using farmer-owned SP equipment (Hennessy *et al.*, 2011a). An increase in the cost of slurry application of these proportions would restrict the level to which these application methods could be adopted by operators other than contractors. The explanation of the sensitivity to the assumed value of R_o is similar to that for V, whereby the lower hourly application rates result in higher fuel and labour costs per unit volume of slurry applied or per unit of NH_3-N abated. The C_{NH3} was also sensitive to the effect of E_e, particularly at lower values of E_e where the marginal effect of change in C_{NH3} was greater than at higher values.

The sensitivity of C_u and C_{NH3} to the effect of varying the additional capital costs inferred by P_e and C_e highlight the importance of machine design and performance that reduce the investment cost in capital, and the power requirement for their operation. The contribution of additional capital costs for the tractor to the total additional capital costs (A_c) (Figure 5.1) also indicates the importance of considering the additional capital cost of the tractor in addition to the application equipment where incentives such as grant aid on capital investment in equipment are being designed to promote the adoption of low-emission equipment. However, the methodology used in this study assumed that the additional costs of the increased tractor power requirement would be required solely for the purpose of operating the slurry application equipment. Therefore, all of the additional capital costs associated with the tractor were included in the slurry application cost. The potential benefits or savings due to having the increased power available for other operations performed using the tractor were not considered, but may exist in some cases. While the tractor will in most cases be used for work other than slurry operation, it was considered that the additional cost would not need to be incurred if the slurry application method was not changed.

Cost savings with reduced mineral N fertiliser inputs due to NH_3-N emission abatement is often viewed as a means of offsetting the cost of low-emission application method adoption. However, the results of this analysis show that there was a net additional cost of adoption after mineral N fertiliser savings were included, even at the higher range of the values of N included. Current agronomic advice in Ireland assumes that larger savings on fertiliser nitrogen can be made by applying slurry to grassland in the spring (February to April) period, rather than in the summer (June and July). The NFRV of slurry applied with SP in summer (May-July) is assumed to be 0.12 kg kg^{-1}, whereas the *NFRV* increases to 0.21 kg kg^{-1} for application in spring (February-April). Low-emission application methods are assumed to increase the NFRV by 0.10 kg kg^{-1} in both spring and summer.

(Coulter and Lalor, 2008; Lalor *et al.*, 2011). Nutrient advice in the UK also assumes a higher NFRV for spring application (0.25-0.45 kg kg^{-1}) compared to summer (0.20-0.35 kg kg^{-1}). The increase in *NFRV* with bandspreading is assumed to be 0.05 kg kg^{-1} (DEFRA, 2010). While these estimates of the NFRV were not adopted directly in this study, they correspond closely with the quantities of NH_3-N abated in the calculations of this study. Based on the assumed value of *T* in this study of 1.8 kg m^{-3}, the NH_3-N conserved was 0.297 and 0.347 kg m^{-3} with TH and TS methods, respectively. This equated to an increase in NFRV due to the application method of 0.08 and 0.10 kg kg^{-1} with TH and TS, respectively. These are in agreement with the effects of TS on NFRV cited above. The corresponding increase in NFRV with SI based on this study was 0.19 kg kg^{-1}.

The main restriction to SP application in spring is the requirement for suitable soil trafficability conditions to coincide with short grass covers so that herbage contamination can be minimised. The low-emission application methods minimise grass contamination by applying slurry in lines rather than on the entire grass canopy. Therefore, they allow greater flexibility of application timing by facilitating application on taller swards (Laws *et al.*, 2002). This results in more spreadland being available for slurry application on the days in spring when weather conditions allow traffic. There is potential for greater savings on fertiliser N costs through adoption of low-emission application technology, as a greater proportion of slurry may be applied in the spring when the nitrogen fertiliser replacement value can be maximised (Lalor and Schulte, 2008). Of the low-emission application methods, the TH and TS methods are considered to be more suitable for Irish grassland, as they avoid potential problems with slurry injection in Irish soils due to variability in stone content, texture, drainage and topography. The TS may also infer additional benefits over TH by reducing the contamination of herbage with slurry, as the shoe coulter is designed to improve the precision of slurry placement at the base of the sward.

Where additional NFRV benefits due to flexibility in application timing allowing application in spring are also inferred by the adoption of low-emission application equipment, the net costs would be reduced as greater mineral N fertiliser cost savings could be achieved (Lalor, 2008). Where application in spring can be facilitated, the NFRV is increased by approximately 0.10 kg kg^{-1}. This equates to an additional cost saving of €0.43 m^{-3} of slurry. Assuming that this increased flexibility application timing and NFRV benefit is achievable with all methods, the additional cost saving would reduce the C_u to €0.16 m^{-3}, €0.80 m^{-3} and €1.48 m^{-3} with TH, TS and SI, respectively. However, Lalor and Schulte (2008) demonstrated that this benefit is more likely with TS than with TH or SI since the TS was considered the most effective machine at reducing sward contamination with slurry.

5.5. Conclusions

The TH method of slurry application was the most cost effective of the low application methods based on the assumptions adopted in this study. The SI method had the highest costs per unit of slurry volume applied, while TS had the highest cost per kg of NH_3-N abated. However, this conclusion was based on assuming a level of NH_3-N emission abatement with TS specific to Irish conditions that is lower than that suggested in other literature sources. The benefit of mineral N fertiliser savings due to NH_3-N emission abatement was not sufficient to offset the total cost of adoption, even when additional benefits of improved flexibility in application timing were taken into account. The sensitivity analysis showed that the factors that had greatest impact on the cost were the assumed NH_3-N abatement potentials, the volume of slurry being applied annually with each machine, and the hourly work rate of the equipment. The capital costs of increased tractor power contributed significantly to the total capital cost of adoption of low-emission equipment.

6

Practical advice for slurry application strategies for grassland systems

S. T. J. Lalor, N. J. Hoekstra, P.N.C. Murphy, K. G. Richards, and G. J. Lanigan, 2012. Proceedings No. 712, International Fertiliser Society, York, UK.

Abstract

Management of animal manures in history has been influenced to varying extents by objectives of maximising nutrient utilisation and minimising environmental impacts. Relatively inexpensive and freely available mineral fertilisers over the past half-century gave rise to a period in which efficient nutrient recycling was not prioritised. However, the emphasis on slurry as a nutrient resource has been re-established following recent increases in fertiliser prices and the increased focus on manure management within European Union (EU) and national environmental policies. Farmers and policy makers are seeking advice and solutions to maximise fertiliser replacement value (FRV) and minimise negative impacts on water and air quality and climate change. This paper focuses on recent research in Ireland on aspects of slurry management. It discusses how slurry management can contribute to achieving the objectives of reducing ammonia (NH_3) emission, increasing nitrogen (N) FRV, and accounting for the residual release of N where slurry is applied annually over long periods. Costs of low-emission application methods are also considered, and emerging research on the NFRV of dilute slurry and soiled water is also discussed. Proposals are made for FRV advice for slurry and soiled water applied with different application methods and at different timings. Farmers should prioritise the distribution of slurry around the farm and application rate based on P and K requirements, and then target cooler and moister atmospheric conditions in spring, when nutrient uptake requirements are highest, in order to maximise NFRV. Application methods such as trailing shoe have been shown to be uniformly effective at reducing NH_3 emissions and increasing NFRV across a range of climatic conditions. However, they are a more expensive strategy than targeting suitable climatic conditions with conventional splash-plate equipment. Managing application timing to target climatic conditions is, in principle, a cost effective means of increasing NFRV. However, alternative low-emission application methods may be necessary where high targets for NFRV are set, or when suitable climatic conditions do not occur so often. The application of this research has had a significant impact on slurry management at farm level in Ireland. While the adoption of low-emission application methods has been very low, despite being incentivised in a number of national funding schemes, there has been a large shift in application timing, with the proportion of slurry being applied in spring increasing from 34% in 2003 to 52% in 2009.

6.1. Introduction

The application of manures to land is a feature of modern agricultural systems that has persisted for many centuries. The law tracts of the 7th and 8th centuries in Ireland detail the importance and presence of an *otrach* (dunghill) in the *les* (farmstead surrounded by a circular enclosure) (Feehan, 2003). Prior to the advent of mineral fertilisers, manures were a critical soil amendment for improving soil fertility and supplying nutrients to crops. However, while manures are beneficial as a source of nutrients for crops, they can have the negative impacts as a source of pollution. This is a real and significant challenge in modern agriculture. Many historical accounts of agricultural activities refer to manure in terms of its benefits for crop and its environmental consequences. For example, Collins (2008), in his book on the history of amendments to soils for agriculture in Ireland, cites from 1489 highlighting how the pestilence and smells caused by manures in Dublin was preventing the visits of “lords, ecclesiastics and lawyers” to the city; and secondly from 1723 in which Lord Molesworth heralded that dung from beasts “when laid upon the land heartens it extremely”, and that a farmer should supplement his own manure stock by returning from visits to the Market Town to sell corn with his cart filled “with good manure fit for the use of his field”.

In many ways, history shows that we have not moved on very far from this paradox of seeing manures as both a beneficial nutrient source for crops but also a waste and potential pollutant. What did change in developed agricultural economies in the last half of a century was the emergence and widespread availability of mineral fertilisers that have been relatively cheap and reliable sources of nutrients for crops. These fertilisers provided scope for improved precision of nutrient application in terms of rates and timing of application. The availability of this fertiliser technology at a cost effective price has, perhaps, lessened the focus on managing manures efficiently since nutrient loss or wastage from manures has not been as big an issue as it otherwise would be (Smith and Chambers, 1995). However, in more recent times, two principle factors have lead to a renewal in interest in manure management: 1) public concern about environmental impacts and the associated evolution of European and National Policies; and 2) the increasing cost of fertilisers.

Of the manures produced on Irish farms, by far the most important (by volume and nutrient content) are cattle slurry (collected beneath slatted animal housing units, largely over the winter housing period) and soiled water (a dilute slurry produced by regular washing down or runoff from dairy parlours and other hard-standing areas). At present, advice for FRV of slurry in Ireland is very general, with little differentiation between slurry types, application methods and timings. Nutrient advice in Ireland differentiates NFRV between summer and spring application, but makes no reference to soiled water or the effect of application method on NFRV. The potential FRV of residual N release in subsequent years is also excluded (Coulter, 2004; Coulter and Lalor, 2008). There have been a number of recent studies that have investigated these components of slurry application in separate experiments. However, no synthesis of these studies has been conducted to collate the findings into a single framework for FRV advice. The objective of this paper is to review the use of cattle slurry and soiled water in Ireland as grassland fertilisers in the context of management strategies and advice for farmers that can yield positive outcomes for both agriculture and the environment. We review drivers of change in slurry management practices on farms, and collate results of recent research on the effects of slurry on gaseous emissions and grassland agronomy. The paper concludes with practical advice for farmers and policy makers on how best to manage cattle slurry for the benefit of farmers and the wider environment.

6.2. Existing slurry application practice

6.2.1. Cattle slurry

Cattle slurry is a mix of cattle excreta (dung and urine), water and other materials, typically collected in tanks beneath slatted animal housing units over the winter housing period, with typical dry matter (DM) content of 1-10 %. Slurry is defined by the Irish Good Agricultural Practice (GAP) Regulations (Anon, 2010) as having a consistency that allows it to be pumped or discharged by gravity. Cattle slurry is the most common organic fertiliser applied to agricultural soils in Ireland, with over 20 Mt produced and recycled annually (Hennessy *et al.*, 2011a). This contains approximately 100 kt of total nitrogen (N), equating to approximately one third of the total mineral N fertiliser applied annually in Ireland (Lalor *et al.*, 2010). By comparison, less than 20% of the cattle manure is produced as farmyard manure (FYM) (Hyde and Carton, 2005), usually produced in deep litter housing systems that use straw as a bedding material. Cattle are the largest source of animal manures that are applied to land in Ireland, with only approximately 2.4 Mt of pig slurry and 0.17 Mt of poultry manure being applied annually (FSAI, 2008). Soiled water produced on cattle (mainly dairy) farms also compromises a significant volume (approximately 18 Mt yr^{-1}) of organic fertiliser production (FSAI, 2008). However, given the lower total N content (Minogue *et al.*, 2010), soiled water accounts for approximately 10% (10 kt) of the total N that is contained in cattle slurry.

Grazing systems dominate cattle production in Ireland, with animals typically spending between six and nine months of the annual cycle outdoors at pasture. Therefore, less than half of the total animal manure produced is collected, stored and available for application to land. Most manures are applied directly to land after storage, and do not undergo further treatments such as separation or anaerobic digestion.

In most cases, cattle slurry is applied onto grassland on the farm on which the manure is produced. Historically, the slurry has often been returned to areas of the farm used for grass silage (or hay) production. This approach is consistent with the concept of nutrient cycling where the objective is to return the nutrients contained in slurry to the parts of the farm from where the winter feed is harvested. Historically, this has been an operation commonly conducted in summer months after silage crops are harvested, as slurry can be applied to bare grass stubble with minimal risk of subsequent sward contamination. This time of year often corresponds to the time when soil conditions are drier and more conducive to receiving machinery traffic with minimal soil compaction damage and to lower rainfall amounts and decreased risk of runoff of slurry from fields. The results from a survey of farm facilities and manure management practices conducted in 2003 (Hyde *et al.*, 2006) are shown in Table 6.1. It was estimated that in 2003, 83% of cattle slurry was applied to grassland used for conserved winter feed (silage or hay), and that a total of 48% of slurry was applied in summer months, with only 34% applied in spring. The same survey also showed that virtually all (99%) of slurry was applied using the broadcast (splash-plate) application method.

Table 6.1. The percentage of cattle slurry applied in different seasons and to different land uses in Ireland in 2003 (from Hyde et al., 2006).

Land Use		Spring (Feb-Apr)	Summer (May-Jul)	Autumn (Aug-Oct)	Winter (Nov-Jan)	Total
Grassland	Silage/Hay	26	43	11	3	83
	Grazing	5	4	2	2	13
Tillage crops		3	1	0	0	4
Total		34	48	13	5	100

The distribution of slurry around the farm has also been associated with proximity of spreadland to the slurry store, suggesting that strategies to reduce spreading costs can sometimes be prioritised over efficient nutrient recycling. This aspect can be exacerbated by fragmentation of farm holdings which can make some areas of the farm much more convenient for spreading than others. Studies by Murphy (2003) and Fu *et al.* (2010) have shown how soil P and K fertility levels tend to decline with increasing distance from the farmyard and slurry storage facilities, and that this can be attributable to decisions to minimise transport distances for slurry spreading.

6.2.2. Soiled Water

Soiled water, also commonly referred to as dirty water (or dairy shed effluent in some countries), is defined by Pain and Menzi (2011) as water derived from washing of equipment and floors in milking parlours and rainfall run-off from concrete areas or hard-standings used by livestock that is contaminated with faeces, urine, and wasted animal feed, etc. and with a negligible fertiliser value. The Irish GAP Regulations (Anon, 2010) define soiled water as water that has been contaminated with animal excreta, fertiliser, or with machine or vegetable washings, and contains a DM concentration less than 1%, and a biochemical oxygen demand less than 2500 mg L^{-1}. These regulations also take no account of the fertiliser replacement value (FRV) of this material.

In contrast to the definition of Pain and Menzi (2011) that soiled water has a negligible fertiliser value, a survey of soiled water management on dairy farms in Ireland measured average concentrations of DM, total N, P and K of 5.0, 0.59, 0.08 and 0.57 g kg^{-1}, respectively (Minogue *et al.*, 2010). This corresponds to typical nutrient analysis of cattle slurry, diluted by a factor of between six and eight, thereby supporting the consideration of soiled water as dilute slurry. Although soiled water has lower nutrient concentrations than slurry, the volume of soiled water produced per cow on dairy farms is typically higher than the volume of slurry, being approximately 10 and 6 m^3 cow yr^{-1}, respectively. Therefore, soiled water can represent a significant source of nutrients on the farm overall. Despite this, the fertiliser value of soiled water has been broadly overlooked in the majority of advisory information and regulations to date in Ireland. Soiled water is typically applied all year round due to lower requirements for storage capacity (minimum of 10 days in the GAP regulations) and a lack of emphasis on the nutrient value. Application has also been commonly concentrated on fields closer to the farmyard. Application is predominantly by a vacuum tanker with splash-plate, but centralised pumping stations and self-moving irrigators or umbilical systems are also used.

6.3. Drivers of change for slurry management

6.3.1. Slurry value

A primary driver of adapting slurry management practices on farms is the value of slurry relative to mineral fertilisers. In this regard, it is important to distinguish between the potential value that can be assigned to cattle slurry based on certain assumptions of replacement of mineral fertilisers and the actual savings (value) that may be made by a farmer through actual practice. There is also a less quantitative sense of "value" to slurry that comes about through increased awareness of farmers for the nutrient value of slurry that can drive management practices. A switch from viewing slurry as a waste to viewing it as a resource can drive practice change without putting absolute figures on fertiliser replacement values or cost savings.

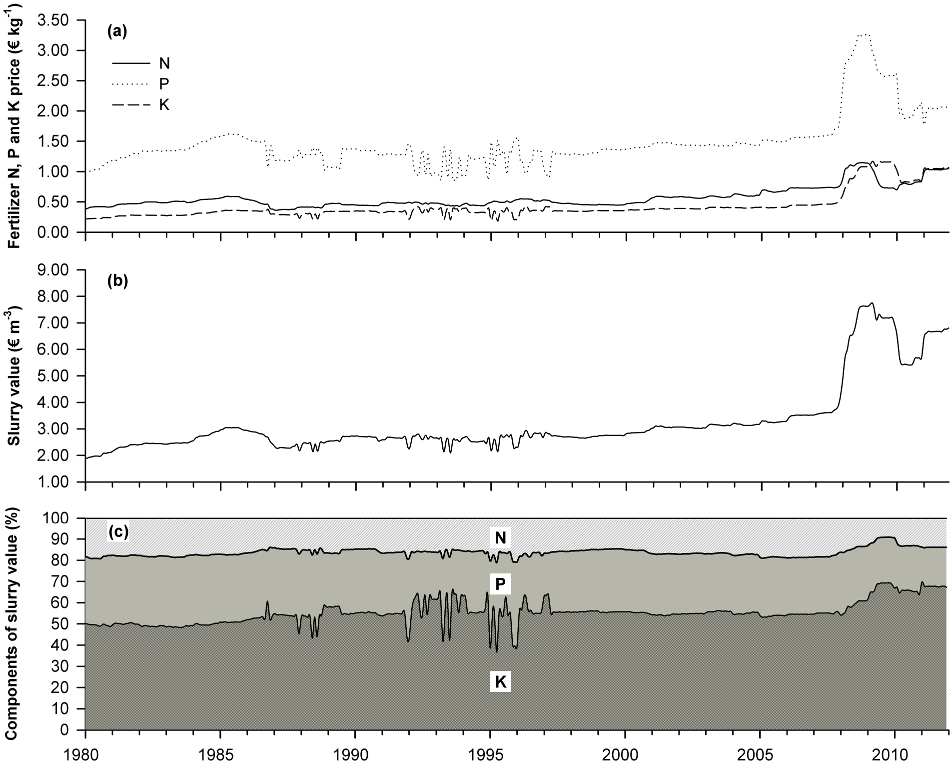

Figure 6.1. Trends in (a) the unit cost of N, P and K in mineral fertilisers in Ireland, (b) the value of cattle slurry based on fertiliser replacement value (FRV) and fertiliser price; and (c) the percentage of total slurry value derived from N, P and K components of slurry, in the period since 1980.

Prices of mineral fertilisers have been highly volatile in recent years. The price of the N, P and K in mineral fertilisers based on multiple regression analysis of retail prices of a range of mineral fertilisers (CSO, 2012), is shown in Figure 6.1a. Based on this analysis, the price of all nutrients have increased considerably and have also been highly volatile during the period since 2008, with N, P and K prices peaking at 1.15, 3.27 and 1.17 € kg^{-1}, respectively, in 2008/09. Recent fertiliser increases can be attributed to increases in both energy costs and global demand for fertilisers. Increased prices and volatility are important considerations as they lead to volatility in farm input costs and profit margins and make farm planning more difficult and risky.

The potential value of nutrients in cattle slurry over time was calculated on the basis of a total N, P and K content in slurry of 3.6, 0.6 and 4.3 kg m^{-3}, respectively, and an assumption of respective FRVs of 25%, 100% and 100% (Coulter, 2004) and is presented in Figure 6.1b. The trend in the economic value of cattle slurry based on FRV follows that of mineral fertiliser price. The value of slurry has also increased considerably in line with fertiliser prices in recent years, peaking at €7.75 m^{-3} in 2008/09, and currently estimated to be €6.80 m^{-3}. This compares to an average value over the period 1980-2007 of €2.76 m^{-3}. This nominal increase in the value of slurry has been a considerable driver of improved slurry use efficiency in Ireland, and a renewed interest at farm level in messages and technologies pertaining to slurry application and nutrient recovery in crops has developed as a result. The trend in the value of slurry shown in Figure 6.1b is based solely on N, P and K, and omits other potential fertiliser benefits arising from organic matter and nutrients such as sulphur (S), magnesium (Mg) and micro-nutrients. The values shown take no account of application costs of either slurry or fertiliser which can be highly variable depending on application technique and distances between the slurry store and the spreadland. Critically, these potential values also do not account for actual farmer practice; the farmer’s ability to achieve the assumed nutrient value from slurry and reduce mineral fertiliser use accordingly and actually realise the cost saving.

While the economic value of slurry has increased, it is important to note that the values presented can only be realised if there is a saving made in the cost of mineral fertilisers by reducing application rates to account for the nutrients in slurry and if the actual slurry management achieves the assumed FRV. The data shown in Figure 6.1c show the trend in the percentage of the total slurry value that is attributable to each of the N, P and K components of slurry. It is worth noting that, although much attention is given to the NFRV and, to a lesser extent, the PFRV of slurry, the percentage of value attributable to N and P are relatively low compared with the value attributable to KFRV. At present, 67% of the fertiliser value of slurry is due to the KFRV, while only 14% and 19% is attributable to N and P, respectively. Therefore, while NFRV is a key consideration of slurry management, the importance of ensuring that the P and K in slurry are fully utilised is also very important to maximising the potential cost savings that can be achieved from the nutrient resource in slurry.

6.3.2. Evolving policy context

Environmental policies related to water quality, greenhouse gases and ammonia (NH_3) directly or indirectly affect manure management practices. Protection of water quality under the Nitrates Directive (Anon, 1991) and Water Framework Directive (Anon, 2000) and associated national legislation such as the GAP Regulations in Ireland (Anon, 2010) refer to slurry directly regarding maximum application rates and storage requirements, prohibited spreading periods and restrictions on application based on weather and soil conditions, topography and distance from water sources and certain hydrologic features. They also indirectly impact on slurry management by way of limits to total nutrient applications in fertilisers, limits on stocking densities and assumptions regarding the NFRV and PFRV of slurry. Implicit in these measures is the intent to maximise the efficiency with which nutrients in slurry are recycled, thereby reducing supplementary mineral fertiliser applications and minimising total nutrient loads and losses to the environment. The GAP regulations In Ireland require that the NFRV and PFRV in slurry are assumed to be 0.40 and 1 kg kg^{-1}, respectively. The target NFRV of 0.40 kg kg^{-1} in the GAP regulations was deliberately set above the pre-existing NFRV in advice of 0.25 kg kg^{-1} to encourage practice adoption to improve NFRV of slurry.

Policies such as the Kyoto Protocol (UNFCCC, 1997), aimed at reducing anthropogenic greenhouse gas emissions, also impact on manure management. Methane (CH_4) and nitrous oxide (N_2O) produced by slurry in storage comprise 12.5% of total agricultural emissions, with further N_2O arising from slurry application. Slurry application management can affect N_2O emissions by the following four mechanisms: 1) direct emissions of N_2O from soil are increased as a result of the N applied in manure; 2) slurry application management that increases the NFRV and reduces the total N load through fertiliser replacement will decrease total N_2O emissions (Schulte and Donnellan, 2012); 3) indirect emissions of N_2O associated with re-deposition of NH_3 volatilised following slurry application; and 4) emissions of N_2O from the slurry N leached into groundwater and surface waters. Slurry application management methods that both reduce NH_3 emissions and increase NFRV have been shown to be positive in reducing greenhouse gas emissions (Webb *et al.*, 2010a; Schulte and Donnellan, 2012).

Air quality targets for reducing NH_3 emissions also impact on slurry management. Unlike water quality and greenhouse gases, where multiple sectors of society and industry contribute significantly, agriculture comprises the vast bulk of national NH_3 emissions (98% in the case of Ireland (Hyde *et al.*, 2003)). Ireland is currently meeting its targets for NH_3 emissions under the National Emissions Ceiling Directive (UNECE, 1999; Anon, 2001). However, future targets currently being negotiated may require measures to further reduce emissions. In this case, the management of land application of slurry with regard to application timing and method will be a key measure (UNECE, 2007).

The common theme running through all these policies is a consistent pressure to reduce the total nutrient loads and surpluses (on an areal basis) in agriculture, and improve the efficiency of recycling of nutrients. The policy focus on this issue has put slurry in the spotlight regarding environmental cross-compliance issues on farms. This has created awareness of both the FRV and the environmental impacts of slurry on farms and moved farmers to be more cognisant of these issues in their slurry application management practices. With this renewed awareness of slurry management comes a need to improve advice to farmers and to policy makers regarding practices and policy measures that can achieve these multiple targets.

6.4. Overview of recent research

In order to improve advice to farmers and policy makers regarding slurry application, a number of factors need to be considered in tandem. In terms of environmental impact, reducing NH_3 volatilisation is a key objective given that it impacts on NFRV, total N loading and greenhouse gas emissions. However, while NH_3 emissions have an effect on the NFRV in the period soon after application, long term residual effects of slurry on N advice in subsequent years are also worth considering. In reducing NH_3 emissions, both application method and timing strategies as well as slurry dilution need to be evaluated and considered, both in terms of efficacy and cost. A number of research studies have been undertaken in Ireland in recent years focussing on these separate aspects of slurry application. The following sections outline some of this research and discuss how it can be collated and combined to provide a basis for practical advice for slurry application to grassland.

6.4.1. Ammonia volatilisation

Research on approaches to reduce NH_3 volatilisation indicates that low-emission application techniques such as injection (deep and shallow) and bandspreading (trailing hose or trailing shoe) are the most consistent methods to reduce emissions (Smith *et al.*, 2000; Huijsmans *et al.*, 2001; Misselbrook *et al.*, 2002; UNECE, 2007; Webb *et al.*, 2010a). Regulations implemented in countries such as Denmark and The Netherlands have made low-emission application methods compulsory by prohibiting broadcast application using splash-plate. While there are wide ranges in the emission reductions that can be achieved by low-emission techniques, the mean reductions compared to broadcast application are typically assumed to increase progressively from trailing hose (35%) to trailing shoe (65%) to injection (70-80%) (UNECE, 2007; Webb *et al.*, 2010a).

Dowling *et al.* (in press) compared NH_3 emissions from cattle slurry following application to grassland using splash-plate (SP) and trailing shoe (TS) in Ireland. Over 10 experiments over three years conducted in the months between April and July, the trailing shoe reduced total ammoniacal N (TAN) loss (NH_3-N emission as a % of TAN applied) by 36%. This was lower than the abatement potential of 65% typically assumed in other literature (UNECE, 2007; Webb *et al.*, 2010a). Emissions with SP ranged from 34 to 83%, with a mean TAN loss of 54%. Emissions with TS ranged from 11 to 68%, with a mean TAN loss of 35%. The temporal profile of NH_3 emissions was also altered with trailing shoe application. Of the total emissions following application, 81% of TAN loss occurred in the 24 hours following application with splash-plate compared with 67% with trailing shoe (Figure 6.2).

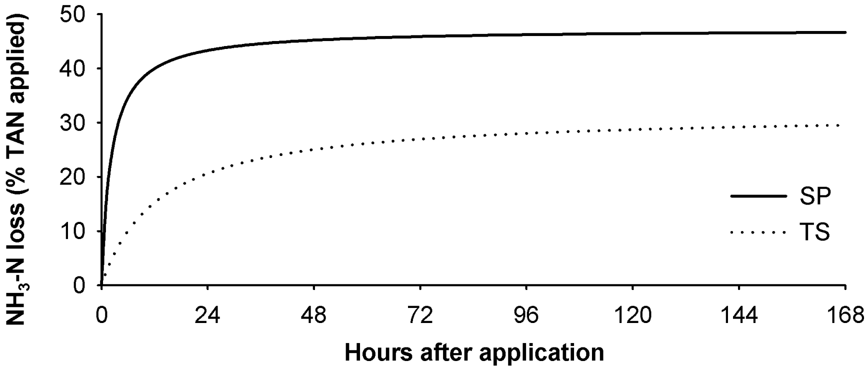

Figure 6.2. Comparison of the predicted NH_3-N loss profile following application with splash-plate (SP) and trailing shoe (TS) application methods based on ten experiments conducted in Ireland (Dowling et al., in press).

Dowling *et al.* (in press) also considered the effects of sward height, climatic conditions and application timing on emissions following application. The height of the sward at the time of application can have a significant impact on emissions due to the effect of sheltering of the slurry by the grass canopy by restricting air movement and intercepting solar radiation. Thorman *et al.* (2008) developed an algorithm for use in combination with the ALFAM model (Søgaard *et al.*, 2002) which predicts that the NH_3 emissions reduction efficiency of trailing hose or trailing shoe application methods compared to splash-plate increases by approximately 5% with every 1 cm increase in sward height. Huijsmans *et al.* (2001) calculated that a grass height increase of 5 cm could reduce NH_3 volatilisation rate following narrow band application by approximately 50%. However, the study by Dowling *et al.* (in press) did not find significant effects of sward height in three experiments that compared emissions following application with trailing shoe to different sward heights. The authors attributed the lack of difference in NH_3 emissions between different sward heights to high rainfall events after application that could have distorted NH_3 emission trends by washing slurry N off the grass canopy.

Climatic factors and slurry characteristics also interact to influence TAN loss (Sommer and Olesen, 1991; Sommer *et al.*, 1991; Moal *et al.*, 1995; Braschkat *et al.*, 1997; Genermont and Cellier, 1997; Menzi *et al.*, 1998; Sommer and Olesen, 2000; Huijsmans *et al.*, 2001; Sommer and Hutchings, 2001; Søgaard *et al.*, 2002; Misselbrook *et al.*, 2005; Dowling *et al.*, in press). Increasing air temperature, wind speed, solar radiation, application rate, and slurry DM concentration have all been shown to increase TAN loss, while increasing relative humidity, rainfall and TAN content can decrease TAN loss. The interaction of these factors infers benefits to managing timing of slurry application to reduce NH_3 emissions by applying when these factors interact to favour lower emissions.

The ALFAM model (Søgaard *et al.*, 2002) has been used to predict TAN loss under combinations of these criteria to give monthly predictions of TAN loss following application of slurry of typical DM and TAN characteristics (Figure 6.3) (Lalor and Lanigan, 2010). These predictions indicate benefits to avoiding slurry application in the warmest and driest months of summer. Emission reductions based on seasonal management of manure application have also been shown in other studies to potentially reduce emissions by approximately 20% compared with previous normal practices (Moal *et al.*, 1995; Reidy and Menzi, 2007). Two separate studies in Ireland have shown a good correlation between TAN loss predicted by the ALFAM model compared to field measurements. However, both studies also showed that ALFAM over-predicts TAN loss under Irish conditions by 11-12 percentage points (Hoekstra *et al.*, 2010a; Dowling *et al.*, in press).

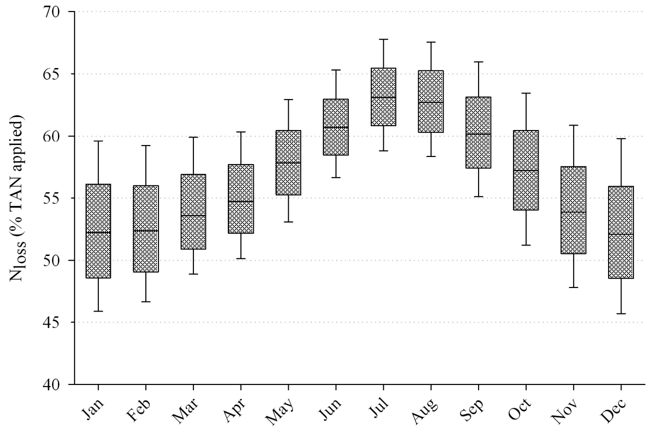

Figure 6.3. Box plot showing median (centre line), interquartile range (boxes) and 10th and 90th percentile (whiskers) of ammonia emissions predictions (N_{loss}) from cattle slurry application using splash-plate for each month based on mean monthly climatic data in Ireland using the ALFAM model (Søgaard et al., 2002; Lalor and Lanigan, 2010).

Slurry DM content as a single manure characteristic has been shown to have a significant effect on TAN loss due to higher rate of infiltration into the soil and reduced exposure of slurry to the air. A comparison of a number of simple models demonstrating the effect of slurry DM on TAN loss is shown in Figure 6.4. Over the range of studies, each 1% decrease in DM concentration in slurry decreased TAN loss by between 4 and 11 percentage points.

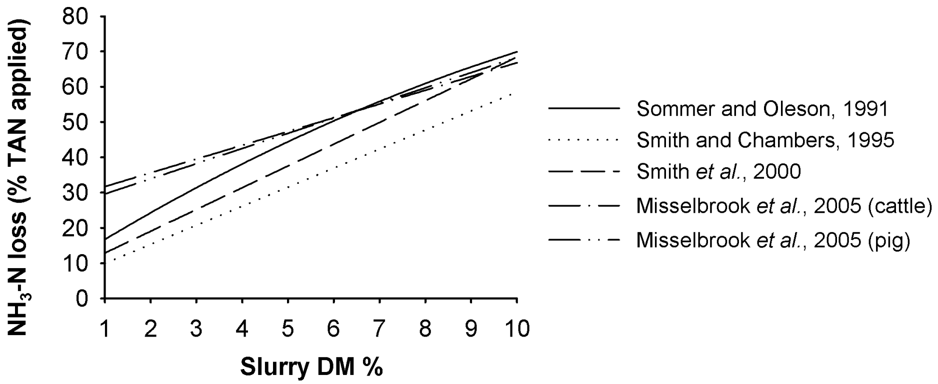

Figure 6.4. Comparison of simple models estimating the isolated effect of slurry DM content on ammonia emissions following splash-plate application.

In addition to seasonal climatic conditions and slurry characteristics affecting TAN loss, the timing of application within a day can also be significant. Ammonia emissions tend to be lower at night due to reduced air movement (windspeed), cooler temperatures and higher humidity. Applications between evening and early morning have been shown to reduce emissions by up to 50% compared with spreading during the middle of the day (Moal *et al.*, 1995; Sommer and Olesen, 2000). In an Irish study, Dowling *et al.* (in press) measured emissions over a 16 hour period after evening application and measured total TAN loss of less than 25% (compared to mean TAN loss with daytime application of 54%). This experiment also found no significant difference between TAN loss with splash-plate and trailing shoe application.

6.4.2. NFRV of slurry in the year of application

Slurry N can become involved in a large number of processes and loss pathways following application. Ammonium (NH_4^+)-N can be immobilised or lost by volatilisation or nitrification followed by leaching or denitrification. Organic N in slurry can be mineralised to NH_4^+-N. However, for simplification, the NFRV of slurry in the crop to which it is applied is largely considered to be a function of the TAN that is not volatilised, as NH_4^+-N in slurry is the principle immediately plant available form of N. Therefore, efforts to maximise the NFRV of slurry in the year of application are mainly focussed on minimising NH_3 loss by manipulating combinations of the factors discussed in section 6.4.1. A question that regularly arises is the degree to which NH_3 that is not volatilised can be considered a replacement for mineral fertiliser. Studies measuring NH_3 emissions often do not include measurements of N uptake in grass or crops, and those that have often conclude non-significant impacts of NH_3 emission abatement technique on the NFRV of the slurry (Lorenz and Steffens, 1997; Smith *et al.*, 2000; Laws *et al.*, 2002; Rodhe and Rammer, 2002).

Research by Lalor *et al.* (2011) (Chapter 3 in this thesis) was undertaken specifically to measure if the reductions in NH_3 emissions reported in literature result in increased NFRV. Over ten experiments on three sites in Ireland, grass DM yield and N uptake in herbage was measured in grass silage crops where slurry was applied with splash-plate and trailing shoe application methods, and with timings in April and June. The slurry was applied using farm-scale application equipment. Across all experiments, the NFRV, calculated based on relative DM yields approximately six to seven weeks after application of slurry treatments, relative to mineral N fertiliser, was 0.10 kg kg^{-1} higher with trailing shoe than with splash-plate. This increase was found at both April and June application timings. Apparent N recovery, and NFRV based on N uptake rather than DM yield were also calculated. However, DM yield has more practical relevance in an agronomic context, as DM yield is usually more critical than N uptake in farming systems, and hence is the main driver of N application rate decisions. Therefore, in giving advice to farmers, NFRV based in DM yield is more appropriate since it is usually the target a farmer will set in terms of grass growth and fertiliser applications.

The mean reduction in TAN loss with trailing shoe compared to splash-plate application reported by Dowling *et al.* (in press) corresponds closely with the increase in NFRV with trailing shoe found by Lalor *et al.* (2011). Assuming a TAN content in slurry equal to approximately 50% of the total N (Beegle *et al.*, 2008), the 19 percentage point reduction in emissions with trailing shoe (35% TAN loss) compared with splash-plate (54% TAN loss) measured by Dowling et al. (in press) equates to an increase of 0.095 kg kg^{-1} of the total N applied in slurry that is not volatilised. Since Lalor *et al.* (2011) estimated that trailing shoe increased NFRV by a very similar proportion (0.10 kg kg^{-1} of N applied in slurry) and given that both studies were conducted using the same application equipment, similar slurries and under similar ranges of climatic conditions, these results suggest that reductions in TAN loss can be assumed to be directly equivalent to improvements in NFRV. However, this is based on the simplified assumption that NH_3 volatilisation is the major loss mechanism contributing to N availability to plants.

Other studies showing significant yield response to alternative application methods include that of Bittman *et al.* (2005), where DM yield and N recovery were increased by approximately 11% with surface banding over aeration slots compared with splash-plate. Studies by Schils and Kok (2003) and Schröder *et al.* (2007) showed increases in the NFRV (calculated based on N uptake) in the year of application of 0.15 to 0.18 kg kg^{-1} with shallow injection compared with SP application methods.

In the study by Lalor *et al.* (2011), the mean NFRV (based on DM yield over the six to seven week period after application), averaged over all sites and years, were 0.21 and 0.12 kg kg^{-1} with splash-plate, and 0.30 and 0.22 kg kg^{-1} with trailing shoe, in April and June, respectively. The NFRV from the slurry applications over cumulative grass harvests for the remainder of the year after application were higher, being 0.32, 0.17, 0.38 and 0.23 kg kg^{-1} for the four respective combinations. While the trailing shoe method had a higher NFRV than splash-plate with both April and June application timings, the NFRV with the splash-plate method in April was similar to the trailing shoe method in June.

The study also included a measurement of NFRV where slurry application was delayed for two weeks and applied into a taller grass sward (Lalor *et al.*, 2013) (Chapter 4 in this thesis). This treatment was included to evaluate whether the reduction in NH_3 emissions reported in other studies due to application in taller grass (discussed in section 6.4.1) resulted in increased NFRV in the grass. The results showed that delaying the slurry application by 7 to 19 days and applying into taller grass swards with trailing shoe had a significant effect of reducing the

DM yield and NFRV compared with earlier application to a grass sward freshly cut to a height of 4-5 cm. The decrease was consistent across April and June timings, with NFRV being 0.11 kg kg^{-1} lower with the tall grass treatment. The mean NFRV (based on DM yield) averaged over all sites and years was 0.20 and 0.11 kg kg^{-1}, in April and June, respectively. There was no significant difference between the NFRV of slurry applied with splash-plate on low grass swards and the slurry applied with trailing shoe when application was delayed and applied into taller swards.

One possible explanation for the decrease in NFRV in the taller sward was the delay in slurry N application. The delayed application may have resulted in the growth of the grass being restricted on these plots prior to the delayed slurry application. This may have reduced the N uptake and subsequent capacity for accumulation of DM compared with the plots that had slurry applied earlier and had a longer growth period after application. However, Hoekstra *et al.* (2010a) conducted an adjacent experiment at one of the sites in two of the years with matching treatments on smaller plots that received no wheel traffic. They found that the recovery of ^{15}N-labelled ammoniacal N from slurry was increased by the later application in taller grass at the first and over cumulative harvests.

Therefore, the delay in N application does not explain the decreases with the taller sward. The decreased NFRV is more likely to be a consequence of the machinery traffic in the taller grass canopy. Frost (1988) measured grass yields in wheel track areas as low as 0.73 times that of non-tracked areas. Douglas and Crawford (1998) measured a reduction in N recovery of slurry from 0.71 kg kg^{-1} with no compaction to 0.53 kg kg^{-1} after compaction. These and other studies associate negative effects on grass yield and N uptake with soil compaction and structural damage, and identify soil wetness as a key indicator of potential soil damage. Frame and Merrilees (1996) highlight the potential direct damage to sward plants and tissues, and concluded that delays between wheel passes of machinery operations following silage harvest should be minimised. While the effect of wheel traffic was not directly measured, the effect of increasing grass height on reducing the NFRV in the taller sward may have been due to increased impact of damage and consequent slower recovery after traffic of taller grass swards. Approximately 20% of the width of the plots in this study received wheel traffic.

Further work is required to identify threshold grass heights that permit traffic for slurry application without reducing yield and N uptake efficiency. Lalor *et al.* (2013) (Chapter 4) estimated that a grass height increase of approximately 1.8 cm was the threshold above which application should be avoided on the basis of NFRV. However, such grass height thresholds are dependent on the design of the application machinery. One of the key considerations is the proportion of the boom width of the spreader that is affected by wheel tracks. The field efficiency of the application regarding headland turning and idle driving will also be significant in determining the total proportion of herbage damaged by wheel traffic.

6.4.3. Residual recovery of slurry N

Slurry can fertilise crops with nutrients both in the year of application and by way of residual nutrient release in subsequent years. Approximately 40-60% of the total N in cattle slurry is in an organic form, derived principally from the faecal matter in the slurry (Beegle *et al.*, 2008). This fraction of the total N is not immediately available for plant uptake, but can become available to plants over time as soil processes of mineralisation and nitrification convert N in soil organic matter into plant available NH_4^+ and NO_3^-. The recovery of this component of the slurry N is considered to be low and is only partly taken into account in fertiliser recommendations. Yet, the recovery of this organic fraction has been shown to contribute to N supply in the year of application and in subsequent years (Schröder, 2005b; Schröder *et al.*, 2005; Bosshard *et al.*, 2009). Schröder *et al.* (2007) estimated cumulative N recovery over four years of 0.47 and 0.32 kg kg^{-1} for slurry applied using shallow injection and splash-plate application methods, respectively. Sluijsmans and Kolenbrander (1977; In Stevens *et al.*, 1997) concluded that approximately 50% of the organic N (25% of the total N) in cattle slurry was ‘easily decomposable’ and would become available for plant uptake in the first year after application, and that the remaining 50% of the organic N (‘resistant’ organic N) would become available in subsequent years.

The results of the experiments by Lalor *et al.* (2011) (Chapter 3) relate to the year of application, and therefore do not account for residual effects from slurry N mineralisation in subsequent years. In a separate study using soil from one of the sites used in these experiments and ^{15}N labelled slurry N fractions, Hoekstra et al. (2011) estimated that when residual N release was taken into account, the slurry N recovered in herbage was increased by 0.03 to 0.04 kg kg^{-1} by slurry N uptake during the second year after application. Of the initial slurry N applied, 0.26 kg kg^{-1} remained in the soil as a potential N mineralisation source after the end of the second year. Hoekstra *et al.* (2010b) used this data to model and predict long-term N recovery rates following repeated slurry applications. In addition to the N recovered in herbage in the initial six weeks after application, it was estimated that residual N recovery rates of between 0.12 and 0.14 kg kg^{-1} were potentially achievable after approximately ten consecutive years of slurry application.

6.4.4. Application timing

Targeting slurry application to conditions of cooler temperatures and higher humidity and rainfall that reduce NH_3 emissions can increase the NFRV of cattle slurry applied to grassland. As 50% of NH_3 is lost in the first 12-24 hours post application, climatic conditions in the hours and days following application are more critical than calendar dates. However, it can generally be assumed that conditions that minimise NH_3 loss, and therefore maximise NFRV, are more prevalent in the autumn, winter and spring months than in summer (Figure 6.3). However, slurry applications in late autumn and winter months are precluded under GAP regulations (Anon, 2010) as a measure to protect water quality.

For replacement of mineral N fertiliser, the months of February to May are the months in which grass growth rates and hence the highest proportions of the total N application rates are advised (Figure 6.5) (Coulter and Lalor, 2008). Additionally, these months do not have the limited grass growth and N uptake and conditions conducive to leaching, runoff and denitrification losses that can be more prevalent following application in autumn or winter. February to May also have lower mean monthly air temperatures compared with summer months. They will therefore have, on average, lower NH_3 loss following slurry application than summer months, thereby making it the ideal time to target slurry application.

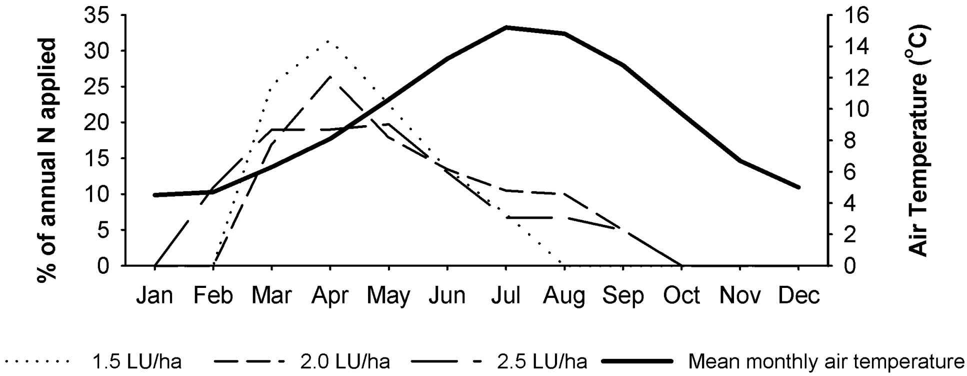

Figure 6.5. Percentage of total annual fertiliser N application advised in each month for grassland at different stocking rates (Coulter and Lalor, 2008), and mean monthly air temperature at the Met Éireann weather station at Mullingar between 1981 and 2010 (Anon, 2012a).

Soil conditions (trafficability and water pollution risk due to wet conditions) and the fear of grass contamination affecting subsequent herbage quality are seen as the main restrictions to spring application. Lalor and Schulte (2008) (Chapter 2 in this thesis) conducted a modelling study to examine the extent to which each of these constraints limits spring application of cattle slurry to grassland for contrasting soils and locations. The availability of spreadland for slurry in spring (between 1 Jan and 10 May) was estimated by applying soil moisture deficit, grass growth and grassland management data to hypothetical farm scenarios with varying meteorological and soil drainage characteristics. The effect of varying the maximum grass cover threshold for application (i.e. the maximum grass cover onto which slurry can be applied without excessive risk of sward contamination) on the available days for spreading is shown in Figure 6.6. On well and moderately drained soils, the availability of spreadland could be increased by an application method such as trailing hose, trailing shoe or shallow injection that would permit slurry application into taller swards with minimal risk of herbage contamination. However, on poorly drained soils, being able to apply slurry in taller swards did not have any effect, as soil trafficability is the main limiting factor. Soil trafficability is a major limitation on all soil types, and application methods that reduce soil compaction damage (such as umbilical systems or reduced ground pressure tyre specifications) may also increase the opportunities for application in spring.

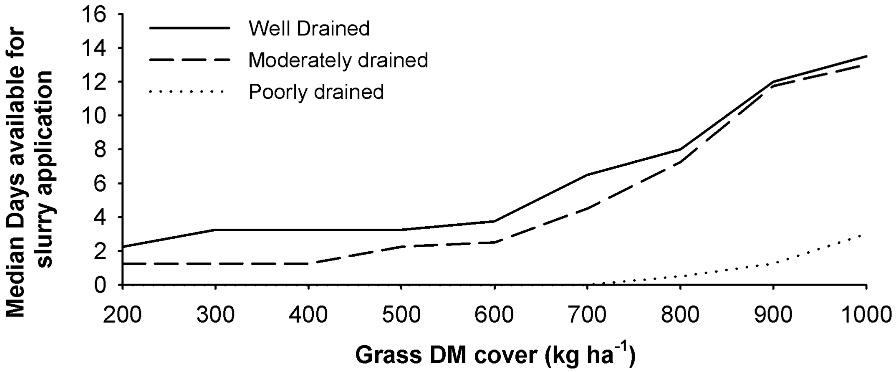

Figure 6.6. Effect of maximum grass cover threshold on the median number of days with ≥ 20% of farm available for slurry application between 1 Jan and 10 May (Lalor and Schulte, 2008).

It has also been shown that the increased costs of trailing shoe over splash-plate means that additive NFRV benefits of both application method and timing are required in order to offset the increased costs of these low-emission application methods (Lalor, 2008). Low-emission application methods may facilitate more application in spring by allowing application in taller swards. However, the findings of Lalor *et al.* (2013) (Chapter 4 in this thesis) suggest that the NFRV benefits of application method and timing are not additive in these conditions. The NFRV of the trailing shoe in taller grass swards becomes more comparable with splash-plate due to damage to the sward and soil by the machinery traffic. The NFRV over cumulative harvests was higher with application in April to tall swards than in June in optimum sward conditions. Therefore, positive benefits from application in April rather than in June could overcome the negative effect where the application in April is only possible if applied in a taller herbage canopy.

In cases where a farmer is currently applying slurry with splash-plate in June, but has soils suited to spring application, switching application from June to April with splash-plate would have NFRV benefits equal to that of switching to trailing shoe application within the June timing. Therefore, switching application timing to spring may well be a more cost-effective measure to improve NFRV than switching to more expensive application methods, depending on circumstances.

6.4.5. Dilute slurry and soiled water

The efficiency with which N is taken up and retained in herbage after application of soiled water can result in relatively higher NFRVs than are achievable with slurry. A study by Minogue *et al.* (submitted) investigated the NFRV of dairy soiled water by measuring DM yield in plot experiments receiving soiled water and N fertiliser as calcium ammonium nitrate (CAN) on two contrasting soil types. Soiled water and CAN fertiliser were applied monthly from February to September. The results showed that the NFRV of soiled water was estimated to be 0.80 kg kg^{-1}. Unlike with slurry, the NFRV was consistent across application timings, with no reduction in NFRV observed in summer months. The soiled water having a higher NFRV than slurry was expected given that the lower DM concentration in soiled water would reduce NH_3 volatilisation through improved infiltration into the soil. The authors identified that approximately two thirds of the total N in the soiled water applied in the experiment was in the organic form. Therefore, the apparent availability of the organic N in the soiled water may be higher than that of slurry, although the reason for this is not definite. The study highlights the potential benefits of diluting slurry as a mechanism to improve NFRV. This might be possible on farms where soiled water is already being produced and could therefore be mixed with slurry to reduce the DM content prior to spreading without increasing the overall storage requirements or spreading costs for both materials on the farm.

What remains unanswered from these experiments is the NFRV that can be assumed for slurries of intermediate DM concentration. The studies of Lalor *et al.* (2011; 2013) (Chapters 3 and 4 in this thesis) applied slurries with DM concentrations ranging from 6 to 8%, while the study applying soiled water (Minogue *et al.*, submitted) used material with DM concentration less than 1%. However, given the linear effects of DM on TAN loss found in previous studies (Figure 6.4), and given that those studies included slurry DM concentrations in ranges of approximately 1 to >10%, it may be plausible to assume that the NFRV will increase linearly with decreasing DM concentration. It is also likely that the effect of application method and timing on NFRV will become less significant as the DM concentration decreases. However, such an assumption would require validation with field experiments studying grass DM yield responses with slurries across a range of DM concentrations and application timings and methods.

At a practical level for farmers, these observations suggest a possible effective strategy for farmers in the context of slurry management with minimal storage costs. A farmer may spread higher DM slurry in spring when tanks tend to be full after the winter housing period and the climatic conditions will maximise the NFRV. Then, when animals go out to pasture and more slurry storage becomes available, the dilution of any remaining slurry with soiled water will improve the NFRV of slurry that remains to be applied in summer months. This would also assist the farmer to have storage tanks emptied during the summer months in advance of the winter housing period while also achieving high NRFV. The overall costs of slurry application would go up if the slurry is diluted with clean water because the overall volume of material to be managed would increase. However, where a farmer can dilute slurry using soiled water, the cost impact should be low since the combined volume of soiled water and slurry would be unchanged.

6.4.6. Greenhouse gas emissions

Slurry management can play an important role in the abatement of agricultural greenhouse gas emissions. Schulte and Donnellan (2012) identified low-emission application methods as a measure to reduce the carbon footprint of Irish agriculture. A shift in practice to 67% slurry application in spring and 50% adoption of trailing hose was estimated to reduce annual emissions by between 0.036 and 0.056 Mt of carbon dioxide equivalents (CO_{2eq}) per annum, depending on the system boundaries, at an annual cost of €5.9 million. Trailing shoe adoption rather than trailing hose is estimated to increase abatement slightly up to 0.041 to 0.065 Mt CO_{2eq}, but comes at a higher cost of €12 million per annum. The analysis highlights that adopting low-emission application methods is a high cost strategy for reducing greenhouse gas emissions. Increasing NFRV and offsetting mineral N fertiliser by improving application timing is more cost effective.

The use of low-emission technologies such as trailing shoe and injection have been hypothesised to result in increased N_2O emissions due to higher soil ammonium pools that can be readily nitrified and subsequently denitrified. However, while there is direct evidence of an increase in N_2O emissions following injection (Wulf *et al.*, 2002; Webb *et al.*, 2010a), there are conflicting reports in terms of increased N_2O following slurry application with trailing hose or trailing shoe (Wulf *et al.*, 2002; Perala *et al.*, 2006). These variations in N_2O emissions when trailing hose, trailing shoe and broadcast methods were compared indicates that the extent of increase associated with lower volatilisation may be over-ridden by other environmental factors, such as soil moisture and/or temperature. As a result, timing of application may be a larger factor in the balance between NH_3 and N_2O loss.

Studies comparing spring, summer and autumn application have shown that the lowest direct N_2O emissions were with application in summer. When indirect N_2O from NH_3 was included, the lowest total emissions were following spring application, with the highest following autumn application. This was due to lower rates of sward uptake, high soil moisture and high windspeed promoting volatilisation (Bourdin *et al.*, 2010).

6.4.7. Cost benefit implications

Only 34% of the available slurry was applied in spring (February to April) in Ireland in 2003 (Hyde *et al.*, 2006), suggesting that the NFRV benefits of spring application were not fully exploited. However, not all soils are accessible for spring application due to soil trafficability or pasture contamination restrictions (Schulte, 2006; Lalor and Schulte, 2008). While switching both application timing and method simultaneously would give the highest overall NFRV, the capacity within this strategy to recover the additional cost of trailing shoe application merits further investigation. Other methods for overcoming application timing restrictions due to soil trafficability, such as umbilical application systems that avoid heavy tanker traffic on fields, or systems for reducing ground pressure from machinery traffic, may also be beneficial and cost effective.

A study by Lalor (in prep) (Chapter 5 of this thesis) estimated additional unit costs of low-emission application method adoption on the basis of slurry volume and NH_3 abatement. It was assumed in the study that the equipment was only financially viable at a contractor level and therefore estimates did not include farmer-owned equipment. The trailing hose method was the most cost effective of the low application methods based on the assumptions adopted in the study both in terms of slurry volume (€0.59 m^{-3}) and of NH_3 abatement (€2.00 kg^{-1}). The shallow injection method had the highest costs per unit of slurry volume (€1.91 m^{-3}) applied, while trailing shoe had the highest costs per kg of NH_3-N abated (€3.55 kg^{-1}). However, this conclusion was based on assuming a level of NH_3-N emission abatement with trailing shoe specific to Irish conditions (35%) that is lower than values of up to 60-65% based on other data sources (Anon, 2003; Webb *et al.*, 2010a).

The benefit of mineral N fertiliser savings due to NH_3-N emission abatement was not sufficient to offset the total cost of adoption, even when additional benefits of improved flexibility in application timing were taken into account. The sensitivity analysis showed that the factors that had greatest impact on the cost were the assumed NH_3-N abatement potentials, the volume of slurry being applied annually with each machine, and the hourly work rate of the equipment. The capital costs of increased tractor power contributed significantly to the total capital cost of adoption of low-emission equipment.

6.5. Practical advice for farmers

6.5.1. Fertiliser replacement values

Based on the findings of these research studies a proposed revision to the FRV advice for cattle slurry and soiled water application in Ireland is shown in Table 6.2. The advice is derived to reflect the numerous aspects of slurry management regarding application method, DM, first year and residual effects. The advice is also structured to be cognisant of all the nutrients that contribute to the economic value of slurry. In the interest of simplicity, and in keeping with other examples in nutrient advice such as in the UK (DEFRA, 2010), FRV values have been rounded to the nearest 0.05 kg kg^{-1}.

The advice for PFRV and KFRV has been fixed at 1 kg kg^{-1}. This means that P and K in slurry are considered to have fertiliser efficacy that is equal to mineral P and K fertiliser. This is a departure from historic advice given for P and K in Ireland (Coulter, 2004) and in the UK (DEFRA, 2010) where lower FRV's have been used, particularly for PFRV. However, the GAP regulations in Ireland (Anon, 2010) include limits on P usage, and prescribe a PFRV of 1 kg kg^{-1}.

The NFRV of slurry N is considered in three categories. Where a farmer only wishes to consider the NFRV for the next grazing or grass silage crop, then the short-term NFRV is appropriate. In this case, the farmer needs to know how much of the total N fertiliser requirement of the grass crop can be supplied by the slurry. These rounded values are based on the studies by Lalor *et al.* (2011; 2013) (Chapters 3 and 4 in this thesis). Where a farmer is concerned about the impact of slurry on the total annual application rate of mineral N in a field receiving slurry, the medium-term NFRV should be used, as this will be the reduction in the total annual mineral N fertiliser application that the farmer should make as a result of the slurry application. The difference between the short-term and medium-term NFRV ranges from 0.10 to 0.00 kg kg^{-1} and is dependent on the time of application. Slurry applied earlier in the year will have a longer period of time available to have organic N mineralised and released in plant available forms for uptake.

Table 6.2. FRV advice for N, P and K for combinations of application method and timing for cattle slurry and soiled water under Irish conditions.

Application Method	Slurry DM	Application timing	NFRV (kg kg^{-1})			PFRV (kg kg^{-1})	KFRV (kg kg^{-1})
			Short-term[1]	Medium-term[2]	Long-term[3]		
Splash-plate *(Trailing Hose / Trailing Shoe in taller grass)*	7%	Spring	0.20	0.30	0.35	1	1
		Summer	0.10	0.15	0.25		
		Autumn	0.10	0.10	0.25		
Trailing Hose / Trailing Shoe *(in short grass)*	7%	Spring	0.30	0.40	0.45	1	1
		Summer	0.20	0.25	0.35		
		Autumn	0.20	0.20	0.35		
Shallow Injection[4]	7%	Spring	0.40	0.50	0.55	1	1
		Summer	0.30	0.35	0.45		
		Autumn	0.30	0.30	0.45		
All	<1% (Soiled Water)[5]	All	0.80	0.80	0.80	1	1

[1] Short-term is based on DM yield results of the first grass harvest (i.e. 6-8 weeks grass growth) after slurry application.

[2] Medium-term NFRV refers to the total NFRV in the year of application, and is calculated as the sum of short-term NFRV plus the residual NFRV in the remainder of the first year after application. Residual NFRV is estimated to be 0.10 kg kg^{-1} for application in spring, 0.05 kg kg^{-1} for application in summer, and 0.00 kg kg^{-1} for application in Autumn.

[3] Long-term NFRV should be used to consider total slurry NFRV where slurry has been applied for more than 10 consecutive years. Long-term NFRV is calculated as short-term NFRV plus 0.15 kg kg^{-1}.

[4] NFRV for shallow injection is assumed based on assumed N fertiliser benefits based on NH_3 abatement potential cited in literature. These estimates are not validated under Irish conditions. The NFRV with shallow injection in taller grass is not included.

[5] Soiled water is considered to have no residual NFRV since the short-term NFRV is already very high relative to slurry.

Where a farmer has been applying slurry to the same field for many years, the long-term NFRV should be used to account for additional N released from slurry applications in previous years. The long-term NFRV should be used where there has been a history of consecutive manure application at approximately equivalent annual rates of application for a period of at least ten years. The long-term NFRV is calculated as short-term NFRV plus 0.15 kg kg^{-1}, which corresponds to the value of 0.12 to 0.14 kg kg^{-1} proposed by Hoekstra *et al.* (2010b). This method is a simplified approach to accounting for residual NFRV, as it assumes that a farmer must apply slurry in the current year to gain the residual benefit of previous applications. Where a farmer ceases to apply slurry in a field with a long history of annual applications, then it would still be appropriate to reduce annual fertiliser N application to account for residual NFRV. In this case, a farmer could use an NFRV of 0.15 kg kg^{-1} based on the average annual slurry application rate in the previous years.

Advice for trailing hose and trailing shoe have been amalgamated in Table 6.2 to reflect the fact that the NH_3 emission reductions with trailing shoe measured in Irish experiments (Dowling *et al.*, in press) are similar to those measured for trailing hose in other experiments (Webb *et al.*, 2010a). Slurry application into taller swards with trailing shoe has been shown to have a lower NFRV than if applied in shorter swards that have been freshly cut or grazed. As a result, the NFRV with trailing hose and trailing shoe in taller grass swards is similar to splash-plate under short grass conditions, and are therefore grouped with splash-plate application in Table 6.2. In the absence of Irish data on shallow injection, an NH_3 emission reduction potential of 70% for shallow injection compared with splash-plate has been estimated to confer a 0.20 kg kg^{-1} increase in short-term NFRV over splash-plate application.

Application timing is differentiated between spring, summer and autumn. The differentiation in NFRV with spring and summer application is based on the findings of Lalor *et al.* (2011) (Chapter 3 in this thesis). Conditions in late autumn months may not be as prone to NH_3 emissions as those of summer. However, the reduced opportunity to replace mineral fertiliser (Figure 6.5), and the reduced requirement for fertiliser N by grass at that time of year are considered to justify the inclusion of NFRV advice more in line with summer than with spring application in Table 6.2. Autumn application is also regarded as the lowest medium-term NFRV since there is little scope to capture any residual N released following application late in the growing season. This N will be vulnerable to loss via leaching and runoff or denitrification during the winter period.

The DM concentration in cattle slurry has been indicated in Table 6.2 as 7%. This is in line with average slurry DM concentration based on a number of Irish studies (Tunney and Molloy, 1975; O'Bric, 1991; Coulter, 2004). Soiled water has been included as material with <1% DM concentration, as defined in GAP regulations (Anon, 2010) and in keeping with the typical composition of soiled water on farms as measured by Minogue *et al.* (2010). Given that the short-term NFRV of soiled water is so high relative to slurry, the NFRV is assumed to be fixed at 0.80 kg kg^{-1}, independent of the factors that affect slurry NFRV such as application timing, method and residual N release. Despite the known relationships between NH_3 emissions and slurry DM concentration, there are no additional bands included in Table 6.2 for slurry DM contents higher or lower than 7%. However, this should be a focus for future work.

6.5.2. Priorities for decision making

Much of the commentary and research on slurry application management focuses on issues such as NH_3 emissions and residual N release. This is for good reason given that N is often the nutrient that gets applied in highest quantities to crops, and that slurry and manures contribute to issues surrounding reactive N in the environment. However, as shown in Figure 6.1c, the contribution of N to the total value of slurry based on FRV is predominantly attributable to P and K rather than to N. Therefore, in order to realise the full value of slurry in terms of fertiliser cost savings, the P and K components are more important than N.

The PFRV and KFRV of cattle slurry are only realised if slurry is applied to fields that have a P and K requirement, and if the appropriate reductions in mineral P and K fertiliser applications are realised. Crop type and soil fertility (soil P and K status, determined in Ireland by Morgan's extraction (Coulter and Lalor, 2008)), are the key elements that determine the rate of P and K required in different fields. In the case of grassland, the P and K requirements for silage crops are usually higher than for grazed swards. Since grass silage comprises a significant proportion of the animal diet while indoors on most Irish farms, most the nutrients in the cattle slurry will have originated from silage. Therefore, applying slurry to areas harvested for silage is a sensible strategy to maximise recycling and use efficiency of slurry P and K on farms.

When deciding on how to manage cattle slurry applications on a grassland farm, farmers should be asking the following questions:

1) Where should cattle slurry be applied?

2) What application rate should be applied?

3) When and how should it be applied?

The questions should be asked and answered in this order. 'Where' to apply slurry involves deciding what parts of the farm have the greatest requirements for P and K, making cattle slurry the first option on the farm in order to meet the requirements for these nutrients. A farmer that is applying mineral P or K fertilisers for some fields while applying excess P or K in slurry on other fields is not utilising the slurry to its full potential. Mineral P and K fertiliser should only be used to meet the remaining P and K requirement of the farm after slurry has been distributed and utilised as efficiently as possible.

The application rate should be based on a rate that will not exceed the requirement of nutrients. The P and K requirement will usually always be met by lower slurry application rates than the N requirement in grassland. Therefore, the application rate should not exceed that required to supply either the full P or K requirement.

When the fields that will receive slurry and the application rate are decided, the final question is to decide when and how the slurry should be applied. This question is asked in order to get the maximum return on the NFRV potential of the slurry. 'When' to apply should target climatic conditions that minimise NH_3 loss and maximise NFRV and application earlier in the year to allow a longer period of grass growth for uptake of residual N. 'How' to spread should target application methods that reduce NH_3 emissions provided the cost of these application methods is not prohibitive.

6.6. Impact of research and advice on farm practice

The findings of this research are being widely disseminated to farmers and advisors in Ireland, and farmers have responded positively, particularly on the message of application timing. The adoption of low-emission technologies has been slow, despite them being financially incentivised in recent years in schemes such as the environmental and farm waste management schemes. A survey of manure management practices on farms in 2003 (Hyde *et al.*, 2006) estimated that only 1% of farms were using low-emission application methods. A repeat of this survey in 2009 (Hennessy *et al.*, 2011a) showed that only 3% of farmers (6% of dairy farmers) were using low-emission methods, with trailing shoe being the most common of them. Despite being incentivised through various schemes, the high capital and running costs of these application methods have restricted adoption at farm level.

The message on application timing has resulted in positive changes on farms. The 2003 and 2009 manure management surveys also recorded slurry application timings on farms. In 2003, 34% of slurry was being applied in spring. By 2009, this had increased to 52%. Some of this increase in spring application is likely to be due to the impact of the GAP regulations where increased slurry storage capacity on farms and prohibition of slurry application in winter months have resulted in a shift in application from winter months to spring. However, the shift in timing can also be attributed to the degree to which farmers have bought into the objective of improving slurry management for FRV benefits, and capitalised on the benefits of spring application as a low cost mechanism to do so.

6.7. Conclusions

1) Strategies that minimise the emissions of NH_3 after application, such as low-emission application methods, application in cool moist conditions (typical in spring), and reducing slurry DM concentration can increase the NFRV of cattle slurry applied to grassland. Variation in these factors results in a wide range in the advice for NFRV in slurry and soiled water (0.10 to 0.80 kg kg^{-1}).

2) Application timing and reducing the slurry DM concentration are strategies to increase the NFRV of cattle slurry and are potentially lower cost options than adopting low-emission application methods. Application in spring rather than summer increases the short-term slurry NFRV by 0.10 kg kg^{-1}.

3) Residual N release in the year of application and from consecutive applications over time can contribute to increase the overall NFRV of slurry applications. These benefits can increase NFRV by up to 0.15 kg kg^{-1}, and should be factored into NFRV advice.

4) The window of opportunity for slurry application in spring, when prevailing climatic conditions and grass requirements for N are likely to optimise NFRV, can be increased by low-emission application methods that permit slurry application with reduced grass contamination in taller grass canopies.

5) The NFRV benefits of low-emission application methods can be negated when slurry is applied to taller grass swards. Delaying the application of slurry and applying into taller canopies with trailing shoe resulted in the NFRV being equal to that of slurry applied with splash-plate.

6) Soiled water and dilute slurry can be a significant source of nutrients on farms, especially when produced in large volumes such as on dairy farms. The NFRV of soiled water has been measured to be approximately 0.80 kg kg^{-1}, with the high levels being attributed to the low DM concentration.

7) Strategies to maximise the FRV of cattle slurry in grassland systems should seek to optimise P and K efficiency as well as N. Targeting slurry applications to parts of the farm with requirements for both P and K should be prioritised.

8) Research and advisory efforts have contributed to an increase in the proportion of slurry applied in spring in Ireland form 34% in 2003 to 52% in 2009.

9) Further work is recommended to define the relationship between slurry DM concentration and NFRV, and to validate the assumptions regarding NH_3 emission reductions and NFRV of slurry applied using the shallow injection method.

6.8. Acknowledgements

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7

General Discussion

S. T. J. Lalor

7.1. Introduction

7.1.1. Background

The management of cattle slurry application in Ireland, as with many other countries, has been hampered by a deficiency of appreciation amongst farmers of the true fertiliser value that slurry can have to supply nutrients to grass and to reduce mineral N fertiliser inputs and costs. This has resulted due to the high input levels of relatively inexpensive and reliable mineral fertilisers during the period up up to the mid 2000’s, when the opportunity cost of improving slurry application management was low. This deficiency has been manifest in the behaviour on farms to apply significant proportions of slurry in summer, autumn and winter when the N fertiliser replacement value (NFRV) is known to be reduced. Also, there is a lack of any significant changes in the use of the broadcast slurry application technique using splash-plate (Hyde *et al.*, 2006).

Pre-existing advice for slurry management on farms in Ireland differentiated between application timing on the basis that slurry applied in spring has a higher NFRV (0.25 kg kg^{-1}) than slurry applied in summer (0.05 kg kg^{-1}) (Coulter, 2004). Similar differences between application timings are included in advice in the UK (DEFRA, 2010). The initiation of the Good Agricultural Practice (GAP) Regulations in Ireland since 2006 have set a target NFRV of 0.40 kg kg^{-1}, which is at the lower end of the range of NFRVs assumed for cattle slurry in Nitrates Action Programmes in the EU (Webb *et al.*, 2010b). These factors combine to indicate that considerable progress could be made on farms to improve the NFRV of slurry applied in grassland systems.

With the onset of legislative targets and increasing mineral fertiliser prices, the emphasis on farms for improved slurry application practice to enhance the FRV of slurry has increased. Application timing and technique offer considerable scope in this regard.

7.1.2. Objectives

The objective of this thesis is to increase the quantitative understanding of the utilisation of N from cattle slurries applied to grassland as function of application method and timing. Application timing was addressed by evaluating the extent to which sward contamination and soil trafficability are limiting N utilisation and the NFRV of the applied slurry. The field work undertaken set out to reinforce the established differentiation in NFRV based on timing, and to measure NFRV using trailing shoe as a low-emission application method. The interaction of method and timing was also investigated to elucidate how factors of timing, application method and sward height, all of which have been shown to impact on ammonia (NH_3) emissions, interact to affect the NFRV of the slurry when applied to grass swards. Since economics on farms are a driver of practice adoption, an economic assessment was also undertaken to investigate the cost effectiveness of low-emission application systems to improve the NFRV of slurry. Finally, the research findings from these studies were collated with other research findings in Irish and International literature to formulate practical advice for farmers in using slurry more effectively on farms to enhance the FRV of the N, P and K in slurry.

7.2. Research Approach and Main Findings

The study combined desktop modelling with field experimentation, to collect data under Irish soil and climatic conditions and management systems. Results of the study and those of related studies were ultimately synthesised into practical advice to farmers (in Chapter 6).

Studies that examined low-emission methods, particularly trailing shoe, in terms of slurry N utilisation by grassland and NFRV benefits, were absent and basically initiated this study. Data to support strategies for improving how farmers could exploit the NFRV benefits of improving application timing was assessed through farm system modelling of grazing patterns and sward growth and utilisation, and by field experimentation of slurry application scenarios of timing and sward height interactions. The cost effectiveness of low-emission application methods was assessed using the BREF methodology (Anon, 2003).

Volatilisation of NH_3 following slurry application was not investigated within this study as previous studies have shown the benefits of low-emission application techniques in reducing volatilisation (Smith *et al.*, 2000; Misselbrook *et al.*, 2002; Webb *et al.*, 2010a). Research pertaining to NH_3 volatilisation following cattle slurry application was also being undertaken in Ireland at the time while this work was underway (Dowling *et al.*, in press).

7.2.1. Modelling the opportunity for spring application

By reducing the effect of slurry contamination of the herbage, the model described in Chapter 2 showed that low-emission application methods offer more flexibility for application of slurry in spring compared to the more commonly used splash-plate application method. However, the effect is strongly dependent on soil drainage class and associated grassland management system. Well and moderately drained soils show a relatively large advantage with low-emission methods, with up to a four-fold increase in the median number of days available for slurry application in spring. Poorly drained soils showed no appreciable difference between application methods. Of the low-emission application methods compared in this study, the trailing shoe method showed the largest advantage in terms of allowing the greatest number of available days for application of slurry in spring. However, this was based on the assumption that the trailing shoe would be the optimum machine choice for reducing herbage contamination. The study showed that soil trafficking in the spring is a key constraint to optimizing the NFRV of slurry by applying in spring, with potential for improvements in application timing being confined to well and moderately well drained soils. However, while poorly drained soils account for approximately one third of the Irish agricultural soils (Gardiner and Radford, 1980), it is true that many farms would contain a variety of soils ranging across soil drainage classes, which might offer scope for application in spring to some areas on many farms.

7.2.2. Field studies

The combined effect of application timing, method and grass height on NFRV, as measured in the field studies (Chapters 3 and 4), is shown in Figure 7.1. The metric for measuring efficiency of slurry N use on farms can impact on the nominal value of slurry N efficiency being recommended for farmers under different application management scenarios. Discussing slurry N efficiency or recovery on the basis of N uptake (calculated as apparent N recovery (ANR) in Chapters 3 and 4 of this thesis) does not fully represent the fertiliser replacement value, as it requires adjustment to account for the efficiency of recovery of mineral N fertiliser under the same conditions. The measurement of NFRV based on N uptake ($NFRV_N$) which takes account of the ANR of mineral N fertiliser is a better indicator of the fertiliser replacement value, as it reflects the potential of the slurry N to replace N uptake from mineral N fertiliser. In many cases, the ANR of mineral N fertiliser will be less than 1 kg kg^{-1}, which will result in $NFRV_N$ being nominally higher in value than ANR_s. This often presents a challenge when comparing results of published experiments, as it is critical to ensure consistency of metric used in the comparison of N recoveries and efficiencies. Expressing NFRV on the basis of DM yield ($NFRV_{DM}$) also accounts for the efficiency of the mineral N fertiliser, but utilises the DM yield response curve rather than the N uptake response curve for calculating relative efficiencies. The NFRV as measured by DM yield ($NFRV_{DM}$) is selected as the most useful NFRV measurement for the basis of nutrient advice, since it is DM yield that is of most immediate and recognisable consequence to a grassland farmer. Existing GAP regulations in Ireland are based on NFRV, and not on ANR.

The results of the field experiments showed that there was a measurable increase in NFRV with trailing shoe when applied on the same day and sward height conditions as splash-plate Chapter 3). However, there was a decrease in the NFRV when slurry was delayed by two weeks and applied into a taller grass canopy (Chapter 4). In the case of the delayed application with trailing shoe, the NFRV results were similar to the results obtained from splash-plate application (Figure 7.1). The reduction in NFRV when applied into taller grass swards was contrary to the result expected, since taller grass or crop canopies have been shown to reduce NH_3 volatilisation in other studies (Sommer and Olesen, 2000; Misselbrook *et al.*, 2002; Thorman *et al.*, 2008). However, it was concluded in this study that the damage to the sward canopy caused by the machinery traffic was the main factor that contributed to the decrease in NFRV.

The difference in NFRV between spring (April) and summer (June) application was found to be smaller (approximately 0.10 kg kg^{-1} across application methods) in these experiments than was assumed in previous advice (Coulter, 2004) (0.20 kg kg^{-1}). However, the benefit of application earlier in the year was significant, and was even more apparent when cumulative harvests over the full growing season after application (Figure 7.1b) were considered in addition to the first harvest period (Figure 7.1a) which only accounted for a growth period of 6-8 weeks post-application. Analysis of the differences between application timings in the field experiments had to account for the data being unbalanced in terms of sites and application timings, since there were more applications in June than in April in the dataset. The same was true for comparisons of soil types since the Kilmaley site was only used for one year in the experiment. Where differences between sites were significant, there was a tendency towards higher NFRV on the well drained soil in Moorepark, Co. Cork compared with the other two sites which were less freely drained. This may be explained by conclusions of other studies (Søgaard *et al.*, 2002; Sommer *et al.*, 2003) where increased speed of infiltration of slurry into soil was considered an important factor for reducing NH_3 volatilisation.

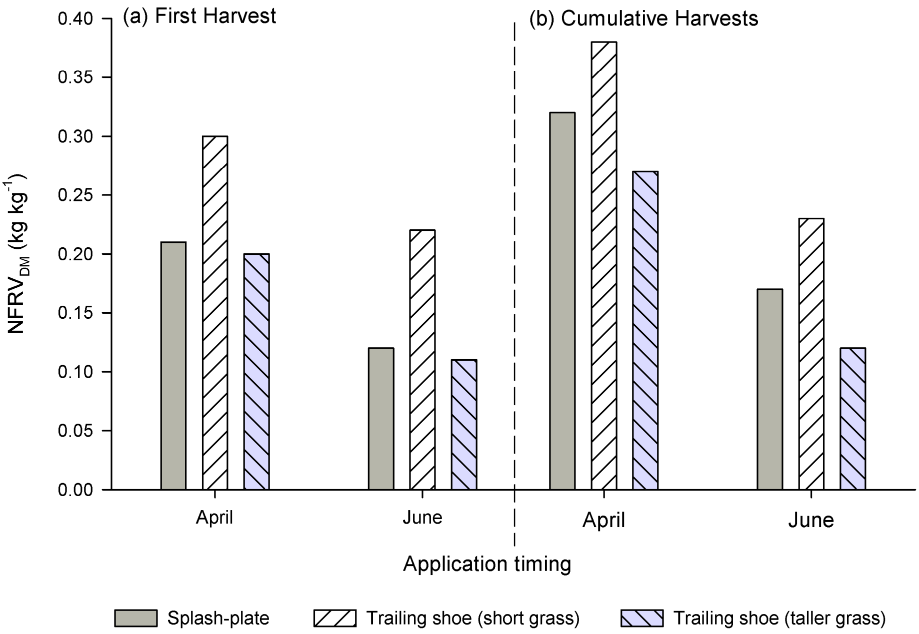

Figure 7.1. Combined effect of application timing, method, and grass height on NFRV of cattle slurry (Lalor et al., 2011; Lalor et al., 2013) (Chapters 3 and 4 of this thesis).

The omission of other low-emission application methods that could be used on grassland, such as band-spreader (trailing hose), or shallow injection is a limitation of these experiments. While other methods were considered for inclusion, the experiment needed to be confined to a single application system due to cost and logistical considerations. The trailing shoe was selected as the optimum method for use in grassland systems as it maximised the reduction in herbage contamination compared to band-spreading or trailing hose. Trailing shoe also reduces the draught power requirement and difficulties associated with stony and/or variable soil type (which are common to Irish grasslands (Gardiner and Radford, 1980)) compared to shallow injection. However, in reality, the differences between low-emission application equipment can be subtle, and the distinction, particularly between band-spreader or trailing hose and trailing shoe, can be a function of the manufacturers labelling as much as by the actual functioning of the equipment. The principle of applying the slurry in a way that minimises the surface area exposed to the air and the contamination of the herbage with slurry are the key considerations. In general, trailing shoe should perform better than band-spreader or trailing hose machines on these criteria.

7.2.3. Economic analysis

The economic analysis was conducted to assess if the increased NFRV was sufficient to recover the additional costs associated with the adoption of low-emission application machinery. The trailing hose method was the most cost effective of the low application methods based on the assumptions adopted in this study. The shallow injection method had the highest costs per unit of slurry volume applied, while trailing shoe had the highest cost per kg of NH_3-N abated. However, this conclusion was based on assuming a level of NH_3-N emission abatement with trailing shoe specific to Irish conditions (Dowling *et al.*, in press) that is lower than that suggested in other literature sources (Webb *et al.*, 2010a). The benefit of mineral N fertiliser savings due to NH_3-N emission abatement was not sufficient to offset the total cost of adoption, even when additional benefits of improved flexibility in application timing were taken into account. The sensitivity analysis showed that the factors that had greatest impact on the cost were the assumed NH_3-N abatement potentials, the volume of slurry being applied annually with each machine, and the hourly work rate of the equipment. The capital costs of increased tractor power contributed significantly to the total capital cost of adoption of low-emission equipment. The sensitivity of additional costs to the volume of slurry being applied annually indicates that the adoption of low-emission techniques would be almost exclusively confined to contractor-based operations. The costs increase by a factor of approximately ten where annual manure volumes more typical of farmer-owned machinery are compared to volumes applied by contractors.

The economic assessment did not consider additional benefits other than fertiliser N savings that could be conferred by low-emission application machinery. Other advantages of low-emission equipment such as:

1) improved lateral distribution of slurry across the bout width due to the uniform distribution of slurry to each pipe outlet;
2) improved flexibility of application timing due to reduced herbage contamination; and
3) reduced emissions of odours after application,

all contribute to the value that an individual farmer might put on a low-emission application method. This is particularly important in Ireland since P is such an integral component of the GAP regulations. With total P inputs being restricted, the distribution of P around the farm in slurry is a critical component of managing soil P fertility levels. The flexibility afforded by low-emission application techniques to apply more slurry into grazed swards during the grazing season, and in a more controlled uniformly distributed way across each field all offer additional benefits to farmers that are not factored into the economic assessment reported in Chapter 5.

7.2.4. Formulating practical advice

In Chapter 6, the results of the experiments and models reported in this thesis were compared to, and combined with, other research findings from Ireland and elsewhere to revise the NFRV advice for cattle slurry application to grassland. This advice also included consideration of slurry management principles that are important for nutrients in slurry other than N, and concluded that cognisance of the PFRV and KFRV are also critical, given that they comprise a larger proportion of the overall FRV in slurry than the NFRV component.

The revised NFRV advice is summarised in Figure 7.2. The revised advice adopts a principle that slurry NFRV should be considered in 3 time-frames. Short-term NFRV is relevant for a farmer who wants to know how much of the next mineral N fertiliser application can be replaced by an application of slurry. The medium (med)-term NFRV is relevant when calculating the reduction in the total annual mineral N fertiliser application that can be made to account for the slurry application. The long-term NFRV should be used where a field has a long history (> 10 years) of receiving annual applications of slurry. This is very typical to a scenario where silage is harvested from the same field each year and slurry is returned.

Application method is considered to increase the NFRV by 0.10 kg kg^{-1} in the case of trailing shoe and trailing hose. Trailing shoe and trailing hose are considered as equal in the advice, since the reduction in NH_3 volatilisation with trailing shoe measured under Irish conditions (Dowling *et al.*, in press) is similar to that found with trailing hose in other studies (Webb *et al.*, 2010a). Shallow injection is included in the advice even though there is no published research data for Ireland to support the findings. An NFRV benefit of 0.20 kg kg^{-1} over splash-plate is assumed for shallow injection on the basis of a typical reduction in NH_3 volatilisation relative to splash-plate of 70% (Webb *et al.*, 2010a). The NFRV benefits of low-emission application methods can be negated when slurry is applied to taller grass swards. Delaying the application of slurry and applying into taller canopies with trailing shoe is assumed to result in NFRV being equal to that of slurry applied with splash-plate at the same application timing.

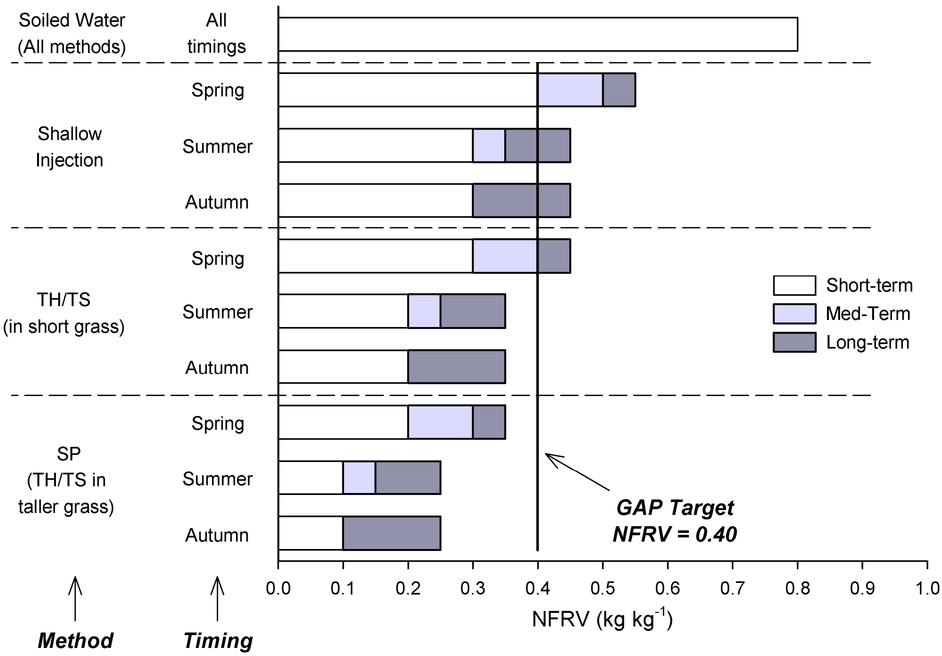

Figure 7.2. Revised advice for short-term (first 6-8 weeks after application), med-term (remainder of year after application), and long-term (where slurry has been applied continuously each year for a period of 10 years or more) NFRV in cattle slurry (7% dry matter (DM) concentration) and soiled water (<1% DM concentration) for spring, summer and autumn application timings and relative to the NFRV target in the GAP regulations in Ireland. (SP = splash-plate; TH = Trailing hose or band-spreader; TS = trailing shoe).

Application timing and reducing the slurry DM concentration are strategies to increase the NFRV of cattle slurry. Application in spring rather than summer increases the short-term slurry NFRV by 0.10 kg kg^{-1}. Residual N release in the year of application and from consecutive applications over time increases the NFRV by 0.15 kg kg^{-1} in the case of long-term NFRV, and by 0.10 kg kg^{-1} (spring applied) and 0.05 kg kg^{-1} (summer applied). The med-term NFRV is increased by application earlier in the year, as it increases the potential for N mineralisation and uptake by the grass in the growing season, and reduces the potential for N losses in the subsequent winter period.

Soiled water and dilute slurry can be a significant source of nutrients on farms, especially when produced in large volumes such as on dairy farms. The NFRV of soiled water has been measured to be approximately 0.80 kg kg^{-1}, with the high levels being attributed to the low DM concentration. No residual benefit has been included for soiled water since the short-term NFRV is so high (Minogue *et al.*, submitted).

7.3. Cattle slurry management on farms

7.3.1. Farm and nutrient management

The message of improving NFRV through managing application timing and using low-emission application methods has been disseminated to farmers in Ireland in recent years following the outcomes of this and other research. Survey data on manure management on farms has been collected within the Teagasc National Farm Survey (NFS). The results of published surveys include data on slurry application equipment and timing in 2003 (Hyde *et al.*, 2006) and 2009 (Hennessy *et al.*, 2011a).

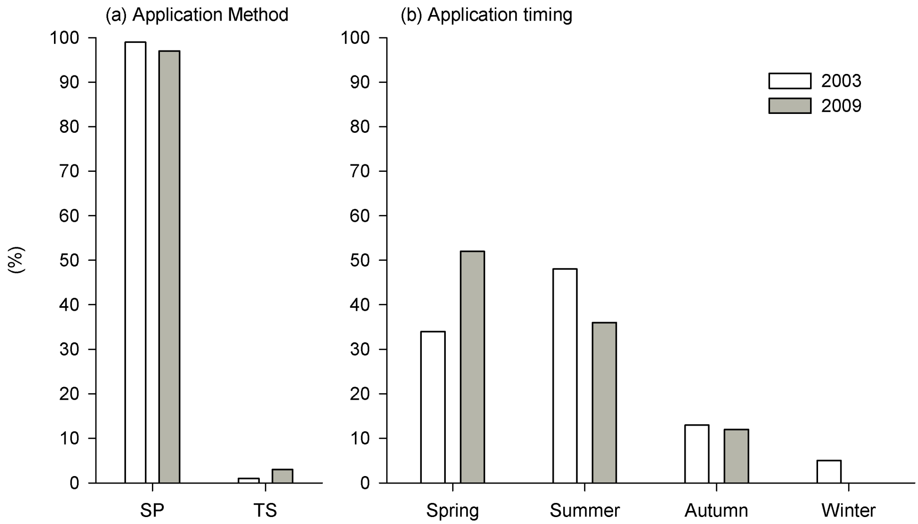

Figure 7.3. Changes in slurry management practices on farms in Ireland with respect to application method (a) and application timing (b) between 2003 (Hyde et al.*, 2006) and 2009 (Hennessy* et al.*, 2011a). (SP = splash-plate; TS = trailing shoe).*

It was estimated that only 1% of farms were using low-emission application methods in 2003. This increased marginally to 3% of farmers (6% of dairy farmers) using low-emission methods in 2009, with trailing shoe being the most commonly used low-emission method (Figure 7.3a). Despite being incentivised through various schemes, the high capital and running costs of these application methods appear to have restricted adoption at farm level.

There have been more significant changes in application timing on farms during the same period (Figure 7.3b). In 2003, 34% of slurry was being applied in spring. By 2009, this had increased to 52%. Some of this increase in spring application is likely to be due to the impact of the GAP regulations where increased slurry storage capacity on farms and prohibition of slurry application in winter months have resulted in a shift in application from winter months to spring. However, the shift in timing can also be attributed to the degree to which farmers have improved slurry management for FRV benefits, and capitalised on the benefits of spring application as a low cost strategy for increasing the NFRV of slurry.

The potential for improved NFRV achieved from this change in application timing towards spring has coincided with a period of reduced mineral N fertiliser usage on grassland farms. The mean N fertiliser application on grassland in Ireland in 2003 of 123 kg ha^{-1} decreased to 86 kg ha^{-1} in 2008 (Lalor *et al.*, 2010). The improved use of slurry N combined with the initiation of the GAP regulations and increasing N fertiliser price during the same period may explain the extent of this reduction in N fertiliser use on grassland. Since 2006, the GAP regulations have imposed a requirement on farmers to account for 0.40 kg kg^{-1} of the total N in cattle manure excreted indoors when calculating mineral N fertiliser allowances for farms. Since the total fertiliser N allowance is capped on the basis of stocking rate, the impact of this has been that best practice is required to achieve the target NFRV from slurry to avoid yield reductions due to restricted mineral N fertiliser usage on the farm.

7.3.2. Timing benefits vs. yield decrease in taller swards

An outstanding anomaly within this study is the potential contradiction between Chapters 2 and 4 with regard to opportunity for slurry application into taller grass swards. In Chapter 2, it is concluded that low-emission application methods, and the trailing shoe method in particular, can increase the opportunity for slurry application in spring by facilitating application in taller swards, thereby facilitating better matching of soil conditions suitable for traffic to slurry application events. However, in Chapter 4, it is concluded that application in taller swards reduces the NFRV due to damage to the grass sward by the machinery.

The question then arises as to whether the benefits of low-emission application to facilitate application in spring are really achievable, given the yield penalty incurred in taller swards. The key consideration here is the combination of application timing and method that determine the NFRV of slurry within a given application management strategy. The ranking of strategies of combined timing and method are shown in Table 7.1 for short-term and med-term NFRV.

For short-term NFRV, there is no benefit in moving slurry application to spring with either a splash-plate or to a taller sward with trailing shoe compared to delaying application until summer and applying with trailing shoe in short grass. Therefore, where trailing shoe is to be adopted irrespective of timing, the potential benefits of trailing shoe to increase the application in spring appear to be negated by the yield penalty due to damage in taller swards. However, if the alternative is to use splash-plate in summer, then applying with trailing shoe to taller swards in spring would be beneficial to the short-term NFRV.

For med-term NFRV, the benefits of spring application become more apparent, as the med-term NFRV from spring application is ranked higher than applications at other timings, irrespective of the application method used (Table 7.1). While applying with trailing shoe in short swards will give the highest NFRV, using splash-plate or trailing shoe in a taller sward will increase the med-term NFRV compared to application in summer. Therefore, the advice to target application in the spring remains valid, as the earlier application provides additive benefits of both reduced NH_3 volatilisation due to weather conditions, and increased residual N release in the year of application due to a longer period available for mineralisation and uptake within the growing season.

Table 7.1. Combinations of application timing and methods ranked in decreasing order of short-term and med-term NFRV of slurry. (SP = splash-plate; TS = trailing shoe).

Short-term NFRV [1] (kg kg^{-1})	Application Timing	Application Method	Med-term NFRV [2] (kg kg^{-1})	Application Timing	Application Method
0.3	Spring	TS (short grass)	0.4	Spring	TS (short grass)
0.2	Spring	SP	0.3	Spring	SP
		TS (taller grass)			TS (taller grass)
	Summer	TS (short grass)	0.25	Summer	TS (short grass)
0.2	Autumn	TS (short grass)	0.2	Autumn	TS (short grass)
0.1	Summer	SP	0.15	Summer	SP
		TS (taller grass)			TS (taller grass)
	Autumn	SP	0.1	Autumn	SP
		TS (taller grass)			TS (taller grass)

[1] Short-term is based on DM yield results of the first grass harvest (i.e. 6-8 weeks grass growth) after slurry application.

[2] Medium-term NFRV refers to the total NFRV in the year of application, and is calculated as the sum of short-term NFRV plus the residual NFRV in the remainder of the first year after application. Residual NFRV is estimated to be 0.10 kg kg^{-1} for application in spring, 0.05 kg kg^{-1} for application in summer, and 0.00 kg kg^{-1} for application in autumn.

It is also important to note that the reduction in NFRV due to sward damage in taller swards will be dependent on the design of the application machinery. One of the key considerations is the proportion of the boom width of the spreader that is affected by wheel tracks. The field efficiency of the application regarding headland turning and idle driving will also be significant in determining the total proportion of herbage damaged by wheel traffic. The boom widths of low-emission slurry application systems for application to grassland in Ireland typically range from approximately 4 to 8 m, with the boom width of 6 m used in this study being quite typical. However, machines are available with booms substantially wider (up to 24 m in the case of trailing hose) than the 6 m wide applicator used in this study. The boom width and the proportion of the sward receiving traffic during application in taller swards will affect the expected impact on NFRV.

7.3.3. Environmental targets

Reducing the N surplus (on an areal and/or unit of production basis) in farming systems is an objective that underlies a number of environmental policies on water and air quality and greenhouse gas emissions (Anon, 1991; UNFCCC, 1997; UNECE, 1999; Anon, 2000; Anon, 2001; UNECE, 2007). The requirements to do so are both environmental and economic in nature, with the cost to society of pollution caused by reactive N in Europe estimated within the European Nitrogen Assessment to be between €70 and €320 billion per year (Sutton *et al.*, 2011). The inefficiency with which slurry N is assumed to be recycled relative to mineral N fertiliser is a major cause for concern, and opportunity for potential improvement in the future. The work included of this thesis highlights strategies available to improve the efficiency of N utilisation from slurry within grassland systems.

7.3.3.1. Ammonia emissions

Policies for reducing NH_3 emissions are currently being revised within the UNECE. While Ireland is meeting its current obligations with respect to emissions, future targets are likely to be more challenging (EPA, 2007). Landspreading of cattle slurry is a key source of emissions. Reducing emissions at landspreading is critical to retaining emission reductions achieved in earlier stages of the livestock production cycle (dietary interventions, housing, storage, etc). Therefore, any policy to reduce NH_3 emissions needs to have landspreading included as an integral component. In this study, the benefits of low cost approaches (often referred to ‘soft measures’), such as optimised application timing management with existing splash-plate machinery, have been shown to be beneficial in terms of NFRV. Farmers have responded by applying more slurry in spring (Figure 7.3). However, two challenges remain with this approach to NH_3 abatement. The verification and administration of a system to account for application timing in a national inventory is a difficulty. Also, the extent of the required reduction in NH_3 emissions may result in targets which ‘soft measures’ cannot achieve. To this end, the adoption of low-emission application methods may be unavoidable in order to achieve future UNECE and NEC targets for NH_3 emissions, despite it resulting in a net cost if mineral N fertiliser and other savings are insufficient to recoup the additional costs.

However, it is important that the potential of least cost solutions are exhausted to their full potential to protect the competitiveness of the agri-sector.

7.3.3.2. Water Quality

The emphasis in water quality policies is moving away from process-driven policy, such as in the Nitrates Directive (Anon, 1991) where instruments were action-based and included measures controlling total N loading and manure storage. Policy such as the Water Framework Directive (Anon, 2000) is now becoming more outcome-driven, focussing more on chemical and ecological parameters in waters (Shortle *et al.*, 2013). The emphasis is shifting towards an increasing focus on water quality standards and targets for receptors, rather than focusing specifically on the activities at source. However, in either case, the focus on reducing N loading remains valid, although may become more targeted based on specific conditions and challenges within regions and catchments. The work included in this thesis does provide information which can contribute to improving the usage of slurry on farms to reduce total N inputs and loadings. However, the work also highlights that single-point targets, such as the NFRV target of 0.40 kg kg^{-1} in the GAP regulations (Anon, 2010), are a blunt instrument that do not account for the variation that can occur in NFRV depending on method and timing. The variation in total nutrient concentrations between slurries also adds complexity, since policies such as the GAP regulations assume standard nutrient concentrations in slurry, whereas advice is usually provided based on FRV of the actual nutrient concentration. Regulatory systems that can take better account of valid restrictions to achieving a single-point NFRV target, such as soil trafficability restrictions of application timing or method, and variations in total nutrient concentrations in slurry, would be of benefit in making the achievement of NFRV targets more realistic and achievable on farms.

7.3.3.3. Greenhouse gases

Improving slurry N also has a role to play in reducing GHG emissions for agriculture, as it contributes to both direct nitrous oxide (N_2O) emissions following N application to soils, and indirect N_2O emissions following the redeposition of volatilised NH_3. Improving NFRV by reducing NH_3 emissions has a neutral effect on total N_2O emissions, since emission factors for both direct emissions from slurry N applied and indirect emissions from redeposited NH_3 are considered to be equal. Application method, particularly shallow injection, can have an effect of increasing the direct N_2O emission factor, but studies are inconclusive as to whether the effect is significant overall (Webb *et al.*, 2010a). Improving the NFRV of slurry can reduce N_2O emission by reducing the total mineral N fertiliser inputs and the associated N_2O emissions. However, in a study of the marginal abatement costs of GHG emissions from the agricultural sector in Ireland, the overall GHG abatement potential from improved slurry application management was estimated to be amongst the measures available that had the highest cost and lowest marginal abatement potential (Schulte and Donnellan, 2012).

7.3.3.4. The fate of unrecovered nitrogen

The question arises from Figure 7.2 as to the fate of the N that is not recovered by the grass crop. For slurry, the range in NFRV across application timings and methods never exceeds 0.55 kg kg^{-1}, even when long-term residual benefits included. The splash-plate method that is most common in Ireland reaches a maximum of only 0.35 kg kg^{-1}. The fate of the remaining N is of interest, particularly given that it will contribute to an N surplus which can result in environmental impacts. The apparent N recovery will be nominally lower than NFRV in most cases, since the apparent recovery of mineral N fertiliser is usually less than 1 kg kg^{-1}. Therefore the proportion of N not recovered in herbage is greater than the proportion of slurry N not accounted for in NFRV.

Ammonia volatilisation accounts for a significant proportion of the unrecovered N. Dowling *et al*. (in press) measured NH_3 emissions of 54 and 34% of TAN applied with splash-plate and trailing shoe, respectively, under Irish conditions. Emissions with splash-plate are similar to those assumed internationally (EEA, 2009). However, the reduction in emissions of 36% with trailing shoe compared to splash-plate is less than was found in other studies, where reductions of more than 50% are reported (Webb *et al.*, 2010a). The full explanation of the lower NH_3 emission mitigation of trailing shoe measured under Irish conditions is unclear, although Dowling (2012) suggests that different slurry DM and TAN contents in the slurries used in Ireland may be a contributing factor. In terms of total slurry N applied, the losses of NH_3 account for up to approximately 25% of the total N applied, where NH_3 losses of approximately 50% and a TAN concentration equal to 50% of the total N are assumed.

Another sink for unrecovered N is explained by the retention of slurry N in the soil organic matter. Hoekstra *et al*. (2011) accounted for 26% of the total slurry N applied in measurements of soil total N taken 63 weeks after slurry application. Almost all of the slurry N was found in the soil organic N pool, with very little (<1%) of the slurry N being present in an inorganic form. Irish grassland soils are considered to sequester carbon, due to soil organic accumulation over time. Nitrogen will also accumulate in soils as the organic matter increases. Since the addition of organic materials, such as slurry, often increases the rate of organic matter accumulation in soils, the retention of N in soil organic matter will therefore account for a proportion of the total N applied.

Losses of N by leaching and denitrification are also likely to account for a significant proportion of the slurry N applied. Hoekstra *et al*. (2011) were unable to account for 21% of the total N applied after N in soil, herbage and volatilisation losses were estimated. It is likely that this N was lost from the soil through leaching and denitrification.

7.4. Concluding remarks

This study was designed to increase the quantitative understanding of the utilisation of N from cattle slurries applied to grassland as function of application method and timing, and thereby to improve the accuracy and reliability of slurry NFRV advice in practice. The study has achieved its objective by creating a revised approach to NFRV advice that now includes differentiation based on application method, timing and residual N release. This represents a major step forward in advice to farmers for slurry management, and farmers have responded through improved management of application timing. The study also showed a significant NFRV response to changing to low-emission application methods. This was not always clearly shown in previous studies. This is a very important outcome for encouraging the use of low-emission application methods on farms. At present, the adoption of low-emission application equipment is not cost effective based on N fertiliser savings. However, changing economics over time may affect this balance. The study shows that the combination of more application in spring and adopting low-emission application methods have a role to play in improving N efficiency from slurry in the future.

7.5. Recommendations for future research

While this thesis includes a comprehensive study and evaluation of the potential for slurry application management to impact on slurry N efficiency, a number of topics emerge that would benefit from further study:

1) Further work is recommended to define the relationship between slurry DM concentration and NFRV, and to refine the NFRV for slurries of intermediate DM concentrations.

2) NFRV measurements over a wider range of slurry application timings would improve the validity of generalising NFRV advice based on season. Measurements over a wider range of application timings would also facilitate

the extension of this dataset to develop a weather-based model for predicting slurry NFRV based on real time weather conditions and forecasts.

3) The NFRV of slurry applied using the shallow injection and trailing hose methods based on NH_3 emissions measurements in the literature requires validation.

4) Further developments of application methods that reduce the adverse effects of soil trafficking will also allow greater opportunities for application of slurry to grassland in spring.

5) Economic assessment of low-emission application methods should be extended to include more complex cost benefit criteria such as improved uniformity of slurry application and benefits from improved slurry application timing afforded by application timing flexibility.

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Summary

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Cattle slurry represents a significant resource on grassland-based farming systems. The objective of this thesis was to investigate and devise cattle slurry application methods and strategies that can be implemented on grassland farms to improve the efficiency with which nitrogen (N) in cattle slurry is recycled. The research focused on slurry application method and timing techniques that have been shown to reduce ammonia emissions following slurry application, and investigated whether the reduction in ammonia emissions translates into an increase in the N fertiliser replacement value (NFRV) that can be assumed from slurry applications. The study also included an economic analysis of the costs and benefits of low-emission slurry application methods, including a sensitivity analysis of the impact of costs that are likely to vary between farms. The study also collated the results of this and other research to devise a practical but effective strategy for slurry application management on grassland farms that considers environmental targets of improving water quality and reducing ammonia emissions with the practical and economic considerations of a farm system.

The findings of this study can be summarised in the following points:

1) Strategies that minimise the emissions of ammonia (NH_3) after application, such as low-emission application methods, application in cool moist conditions (typical in spring), and reducing slurry DM concentration can increase the NFRV of cattle slurry applied to grassland. Variation in these factors results in a wide range in the advice for NFRV in slurry and soiled water (0.10 to 0.80 kg kg^{-1}).

2) Application timing and reducing the slurry DM concentration are strategies to increase the NFRV of cattle slurry and are potentially lower cost options than adopting low-emissions application methods. Application in spring rather than summer increases the short-term slurry NFRV by 0.10 kg kg^{-1}.

3) Residual N release in the year of application and from consecutive applications over time can contribute to increase the overall NFRV of slurry applications. These benefits can increase NFRV by up to 0.15 kg kg^{-1}, and should be factored into NFRV advice.

4) The window of opportunity for slurry application in spring, when prevailing climatic conditions and grass requirements for N are likely to optimise NFRV, can be increased by low-emission application methods that permit slurry application with reduced grass contamination in taller grass canopies.

5) The NFRV benefits of low-emission application methods can be negated when slurry is applied to too tall grass swards. Delaying the application of slurry and

applying into taller canopies with trailing shoe resulted in the NFRV being equal in short-term NFRV to that of slurry applied with splash-plate.

6) Soiled water and dilute slurry can be a significant source of nutrients on farms, especially when produced in large volumes such as on dairy farms. The NFRV of soiled water has been measured to be approximately 0.80 kg kg^{-1}, with the high levels being attributed to the low DM concentration.

7) Strategies to maximise the FRV of cattle slurry in grassland systems should seek to optimise phosphorus (P) and potassium (K) efficiency as well as N. Targeting slurry applications to parts of the farm with requirements for both P and K should be prioritised.

8) Research and advisory efforts have contributed to an increase in the proportion of slurry applied in spring in Ireland form 34% in 2003 to 52% in 2009.

9) Further work is recommended to define the relationship between slurry DM concentration and NFRV, and to validate the assumptions regarding NH_3 emission reductions and NFRV of slurry applied using the shallow injection method.

Samenvatting

Samenvatting

Runderdrijfmest is een belangrijke grondstof op melkveebedrijven. Dit proefschrift beschrijft onderzoek en strategieën die gericht zijn op een efficiënt hergebruik van de stikstof (N) in die mest binnen melkveebedrijven met voornamelijk grasland. Het onderzoek concentreerde zich op toedieningsmethoden en –tijdstippen waarvan verondersteld werd dat ze de emissie van ammoniak (NH_3) zouden kunnen reduceren. Daarbij werd onderzocht of zo'n reductie een positief effect op de N-werkingscoëfficiënt (NWC) van drijfmest zou hebben. Het onderzoek omvatte ook een economische kosten-baten analyse van emissie-reducerende toedieningstechnieken. In dat kader vond een gevoeligheidsanalyse plaats van de effecten van kostenposten die per afzonderlijk bedrijf kunnen variëren. De resultaten van het onderzoek werden gecombineerd met de resultaten van ander onderzoek om te komen tot een praktisch uitvoerbare maar effectieve managementstrategie voor drijfmesttoepassing op grasland. Die strategie houdt rekening met milieudoelstellingen, zoals de kwaliteit van water en de reductie van ammoniakemissie, en doet dit vanuit het perspectief van de praktische en economische overwegingen van een bedrijfssysteem.

De bevindingen van het onderzoek kunnen als volgt worden samengevat:

1) Strategieën die de emissie van NH_3 na toediening van mest beperken, zoals het gebruik van emissie-reducerende toedieningsapparatuur, het uitrijden van mest onder koele en vochtige omstandigheden (typerend voor het voorjaar), en het gebruik van mest met een laag drogestofgehalte, kunnen de NWC van runderdrijfmest op grasland verhogen. De spreiding van factoren leidt tot een brede range aan geadviseerde NWC's voor zowel drijfmest als spoelwater (0,10 tot 0,80 kg kg^{-1}).

2) Vervroeging van het toedieningstijdstip en een verlaging van het drogestofgehalte van drijfmest verhogen de NWC en zijn potentieel kosten-effectievere opties dan het gebruik van emissie-reducerende toedieningsapparatuur. Toediening in het voorjaar in plaats van de zomer, verhoogt de korte termijn NWC van drijfmest met 0,10 kg kg^{-1}.

3) N-nawerking binnen het jaar van toediening en ten gevolge van herhaalde jaarlijkse toedieningen, verhoogt de NWC van drijfmest. Deze bijdragen kunnen de NWC met 0,15 kg kg^{-1} doen toenemen en dienen meegerekend te worden in bemestingsadviezen.

4) In het voorjaar leiden gunstige weersomstandigheden en de behoefte van gras aan N doorgaans tot de beste kans op hoge een NWC. Het aantal geschikte momenten voor de toediening van mest in het voorjaar kan worden vergroot

door het gebruik van emissie-reducerende apparatuur omdat die apparatuur toediening van drijfmest zonder besmeuring mogelijk maakt, ook in hoger gras.

5) De beoogde verhoging van de NWC door het gebruik van emissie-reducerende apparatuur kan verloren gaan als drijfmest wordt toegediend in te hoog gras. Bij uitstel tot dat stadium, leidde de toediening van drijfmest met een sleepvoet tot een even lage korte termijn NWC als de bovengrondse toediening.

6) Spoelwater en met water verdunde drijfmest kunnen een belangrijke hoeveelheid nutriënten vertegenwoordigen, vooral op melkveebedrijven. The NWC van spoelwater bleek ongeveer 0,80 kg kg^{-1} te bedragen. Die hoge waarde werd toegeschreven aan het lage drogestofgehalte.

7) Strategieën ter verhoging van de werking van drijfmest dienen ook met de fosfaat- (P) en kali- (K) benutting rekening te houden. Drijfmest moet vooral aan de P- en K-behoeftige percelen worden toegediend.

8) Onderzoek en advisering hebben het aandeel van de drijfmest dat in Ierland in het voorjaar wordt toegediend, doen toenemen van 34% in 2003 naar 52% in 2009.

9) Aanbevolen wordt om nader onderzoek te doen naar de relatie tussen het drogestofgehalte van drijfmest en de NWC. Ook wordt geadviseerd om de veronderstelde reductie van de NH_3-emissie bij gebruik van zodenbemesters nader te toetsen.

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Go raibh míle maith agaibh.

Curriculum vitae

Curriculum vitae

Stanley Thomas James Lalor was born on the 7th March 1980. He grew up on the family dairy, beef and sheep farm in Camross, Co. Laois, and attended Clonenagh National School in Mountrath, Co. Laois. He attended secondary school at Wilson's Hospital School, Multyfarnham, Co. Westmeath, and subsequently studied Agricultural Science at University College Dublin (UCD) from 1998 to 2002, specialising in Animal and Crop Production. He graduated B.Agr.Sc. (First Class Honours) in June 2002 and continued to study in UCD for his M.Agr.Sc. by research in the subject of Soil Science, graduating in April 2005. In July 2004, he was employed by Teagasc as a Dairy farm advisor in Naas Co. Kildare, and subsequently in the same role in Castleblayney, Co. Monaghan. He has been employed at Teagasc, Johnstown Castle, Wexford since January 2006 as a Research Officer working on nutrient efficiency in agriculture.

PhD Training Certificate

PE & RC PhD Training Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Low ammonia emission application methods can increase the opportunity for application of cattle slurry to grassland in spring in Ireland (2008)

Writing of project proposal (4.5 ECTS)

- Cattle slurry application to grassland – application methods and nitrogen use efficiency (2007)

Post-graduate courses (3.3 ECTS)

- Design of experiments and data analysis; University College Cork (2006)
- Advanced design of experiments and data analysis; University College Cork (2007)

Laboratory training and working visits (0.6 ECTS)

- Visit to manure analysis laboratory facilities; ADAS, Wolverhampton, UK (2011)
- Visit to laboratory and experimental facilities; Irstea, Rennes, France (2011)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Agro-Ecosystems and Environment: ammonia emissions following slurry application (2011)
- Soil Use and Management: decision support tool manure management (2013)

Competence strengthening / skills courses (2.4 ECTS)

- MS Excel; Teagasc (2007)
- Project management; Teagasc (2008)
- MS Access training; Teagasc (2010)
- Time management training; Teagasc (2011)

Discussion groups / local seminars / other scientific meetings (5.5 ECTS)

- Nutrient Management Planning training with Teagasc farm advisors; accompanied policy makers from the Ministry of Agriculture to represent Ireland at these meetings (2006-2012)
- UNECE Expert Panel for Mitigation of Agricultural Nitrogen (EPMAN) & Task Force for Reactive Nitrogen (TFRN); regular contributor to In-service training events for Teagasc farm advisors (2008-2012)
- Teagasc Water Framework Directive Working Group; editor of Teagasc submissions on Ireland's Nitrates Action Programme (2009-2013)

International symposia, workshops and conferences (9 ECTS)

- RAMIRAN Conference; oral presentation; Albena, Bulgaria (2008)
- 16^{th} N Workshop; poster presentation; Turin, Italy (2009)
- ASA-CSSA-SSA Conference; oral presentation; Pittsburg, PA, USA (2009)
- RAMIRAN Conference; poster presentation; Lisbon, Portugal (2010)
- International Fertilizer Society; invited oral presentation; Cambridge, England (2012)

Lecturing / supervision of practicals/ tutorials; (3 ECTS)

- Nutrient management; University College Dublin (2011-2013)

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