NITROGEN FERTILIZER STRATEGIES FOR IRISH GRASSLAND

BY

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A thesis submitted for the degree of

MASTERS (M.Phil)

WATERFORD INSTITUTE OF TECHNOLOGY

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Submitted to Waterford Institute of Technology, School of Science and Computing, Department of Science December 2019

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List of Abbreviations and Symbols

&	And
°C	Degrees centigrade
€	Euro
>	Greater than
≥	Greater than or equal to
<	Less than
%	Percentage
£	Pound
AD	Anno Domini
ANOVA	Analysis of Variance
ARFN	Apparent Recovery of Fertilizer Nitrogen
ANI	Added Nitrogen Interaction
ANR	Apparent Recovery of Nitrogen
AS	Ammonium Sulphate
ASL	Above Sea Level
ASN	Ammonium Sulphate Nitrate
BL	Blanket
C	Carbon
CP	Crude Protein
CAN	Calcium Ammonium Nitrate
C.E.C	Cation Exchange Capacity
cm	Centimetre

Co.	County
CSO	Central Statistics Office
D	Dates
DM	Dry Matter
EEC	European Economic Community
EPA	Environmental Protection Agency
EM	Early to Mid-Rotation
EU	European Union
Fig.	Figure
FYM	Farm Yard Manure
g	Gram
GHG	Green House Gas
H	Harvest
h	Hours
IAH	Immediately After Harvest
H_2O	Water
ha	Hectare
K	Potassium
kg	Kilogram
kt	Kilotonne
L	Litre
LU	Livestock Unit
m	Metre

m^2	Metre squared
MAC	Maximum Admissible Concentration
mg	Milligram
mins	Minutes
ML	Mid to Late Rotation
mm	Millimetre
mth	Month
N	Nitrogen
N0	N uptake in zero-N plots
N_2	Di-nitrogen
N_2O	Nitrous oxide
NBPT	(N-butyl) thiophosphoric triamide
NF	Applied Fertilizer N
NFRV	Nitrogen Fertilizer Replacement Value
NH_3	Ammonia
NH_4^+	Ammonium
NO	Nitric oxide
NO_2^-	Nitrite
NO_3^-	Nitrate
NS	Not Significant
NU	N uptake in fertilized plots
NVZ	Nitrate Vulnerable Zone
O_2	Oxygen

OM	Organic Matter
P	Phosphorus
P-value	Probability
R	Rate
R^2	Coefficient of Determination
S	Sulphur
s.e.m	Standard error of the Mean
SI	Statutory Instrument
SOA	Sulphate of Ammonia
SOM	Soil Organic Matter
SOR	Stage of Regrowth
SW	Soiled water
t	Tonne
UFL	Unite fourragere lait
UK	United Kingdom
WFPS	Water Filled Pore Space
w/w	Weight for Weight
yr	Year

Declaration

No element of the work described in this thesis has been previously submitted for a degree at this or any other institution. The work in this thesis has been performed entirely by the author.

Signature: ____

Date: ____

Acknowledgements

I wish to acknowledge the Teagasc Research and Innovation Centre and Waterford Institute of Technology for allowing me the opportunity to carry out my research work. Additionally, I would like to express my sincere thanks to Dr. Pat Dillon, Head of the Animal and Grassland Research and Innovation Programme, for all the facilities he made available to me.

I would like to express my enormous gratitude to Dr. James Humphreys for all the support and encouragement he has given me throughout this academic journey. I would also like to thank Dr. Imelda Casey for her scientific advice and her patience during the writing of this thesis.

Thanks also to all the researchers over the years that have helped shape my career and developed my scientific understanding, especially, Pat Dillon, Seamus Crosse, Frank Buckley, Franz Aarts, Gary Lanigan, Laurence Shalloo and my good friend Michael Ryan (may he rest peace).

To all the team at Solohead: I could not have done this without all your hard work and endless drive, special thanks to Tommy, Sean, Patrick and Aidan. I must also pay special mention to Flor Flynn in the grassland laboratory for allowing me to litter his laboratory on a weekly basis with grass and to Norann Galvin and Christina Fleming for carrying out chemical analysis on all my samples. I would also like to thank my two Honda Lawnmowers for the hundreds of hours I clocked up on them, may they enjoy their retirement.

Throughout my time in Teagasc I have built up a group of friends whom I hold very dear. They have been there for me through thick and thin and I hope I will have their friendship for all of my life. Thank you, Brendan, Cora, Jimmy, Jack, Kay, Sean, Donagh, Fergal, Jonathan, Grainne, Mary, Bill, Siobhain, Sinead, Tobin, Coleman, Hutch, Alan, Denis (R.I.P), Rob, Orlaith and of course my wife Lisa.

Finally I would like to thank those whom I love. To my parents, Bill and Helen and my sister Orla and brothers Liam and Maurice, I am grateful for all your support and encouragement along the way. Last but not least, to my wife Lisa, who helped me see this through to the end and to our wonderful children, Sarah, Avery and Jude.

This thesis is dedicated to the memory of my grandmother Jane Mc Namara and my cousin John Feeney.

Abstract

The application of mineral fertilizer nitrogen (N) is a quick and convenient way of supplying N to grassland. It is the primary way in which farmers can manipulate grass DM production within a grazing system, as it ensures an adequate supply of N is available to allow grass to reach its full potential yield. Two field-plot studies were carried out on perennial ryegrass swards at two different sites with different soil types (sandy loam and clay loam) in southern Ireland between 2004 and 2006. Their purpose was to examine the effect of various fertilizer N application strategies on grass dry matter (DM) production in spring and throughout the main growing season and also on N uptake, N recovery and N concentration in grass applied with fertilizer N.

Application rate and application date of fertilizer nitrogen (N) are important factors determining grass production response and N recovery by grassland in spring. Study (1) was conducted at two sites in spring 2005 and 2006. In comparison with a non-fertilized (zero–N) control, urea N was applied at rates of 60 and 90 kg N/ha either as single or split applications on eight dates ranging between 11 January and 14 March in both years. Grass was harvested on four occasions between 21 February and 25 April, also in both years. Split fertilizer N applications provided the best outcome in terms of grass DM production, apparent recovery of fertilizer N (ARFN) and cost of additional grass produced compared with single applications. Likewise, in this study the optimum date to commence fertilizer N application was 21 January combined with a second application on 26 February in terms of the cost effectiveness of the fertilizer N input to increase grass DM production.

In grassland it is typically recommended that fertilizer N is applied immediately after defoliation in each grazing/cutting rotation throughout the year. In practice, farmers often deviate from this approach with a ‘blanket’ approach on farms where fertilizer N is applied once per rotation; i.e. fertilizer N is applied to swards at different stages of regrowth across the farm. Study (2) was conducted at two sites in 2004 and 2005. Fertilizer N was applied on 24 occasions throughout each growing season. There were three sets of plots at each site with each set receiving applications of fertilizer N eight times and harvested eight times per year. Fertilizer N application to each set was offset by approximately 10 days following the start of the experiment each spring with overlapping harvests of each set throughout each growing season. Two fertilizer N application strategies were compared: (i) application immediately after each harvest (IAH) in each rotation and (ii) a blanket application once per rotation, which was

represented by the mean outcome of fertilizer N applied at different stages of regrowth (SOR): IAH, early to mid-rotation (EM) and mid to late rotation (ML). Two types of fertilizer N; Calcium ammonium nitrate (CAN) and urea were applied at annual rates of 200 and 300 kg N/ha. Swards were harvested at four week intervals until mid-August, at five week intervals until mid-September and at six to eight week intervals for harvests from mid-October to late November. Fertilizer application strategy, type and rate all had a significant ($P \leq 0.001$) effect on grass dry matter (DM) production. CAN produced higher annual DM yields than urea and differences were greatest during the spring and early summer. Applying fertilizer IAH produced the highest DM yields except where urea was applied at a rate of 300 kg N/ha. A blanket approach to fertilizer N application can be integrated into an annual fertilizer N application strategy between mid-January and mid-March and from July onwards with little or no loss of production provided that fertilizer N is applied IAH at the other time of the year.

These studies work in conjunction to highlight some of the advantages and disadvantages of the use of mineral N fertilizer in pasture-based systems of production in Ireland. The results obtained can be used co-ordinate a planned, season long, approach to fertilizer N application that can optimize the return in terms of grass DM production whilst at the same time minimize the loss of N to the surrounding environment.

This co-ordinated plan highlights three key aspects, (i) that initial fertilizer N applications in spring should involve two smaller applications spread apart from each other rather than one large one, (ii) that there is an appropriate fertilizer type to use at different times of the year and finally (iii) that fertilizer N can be applied using a blanket approach in the first two rounds in spring and the last two rounds in autumn without any negative impact on productivity.

Chapter 1 Introduction

In Ireland intensive grass based dairy enterprises are dependent on the importation of high levels of mineral fertilizer N in order to meet the forage requirements of grazing animals (Dillon *et al*. 2009; Burchill *et al*. 2016).The reason being that at certain periods over the growing season the supply of background N through atmospheric deposition, biological fixation and the mineralisation of N in soil organic matter (SOM) is insufficient to meet the N required for the desired high levels of grass production. As a result of intensification in recent decades mineral fertilizer N has been used in farming to address any imbalance between supply of and demand for N.

Due to the increasing cost of fertilizer and stricter regulations under successive statutory instruments SI 378, 2006, SI 610, 2010, SI 31, 2014 and SI 605, 2017 (Good Agricultural Practice for Protection of Waters) on its use in the last number of years greater emphasis has been placed on the importance of good operational management of imported nutrients such as fertilizer N. This is because the efficient use of such an input has a significant impact on the sustainable economic and environmental performance of Irish grass based systems of dairy production (Vellinga *et al*. 2004; Treacy, 2008; Humphreys *et al*. 2012). Therefore, the central component of good grassland management has become the strategic use of fertilizer N, whereby the supply of N is matched with demand and excessive application is avoided (Humphreys *et al*. 2003a).

In Ireland there is potential for some level of grass growth all year round. Highest levels of growth occur from late spring to late autumn/early winter. However, due to our temperate climate the level of growth over the winter period is relatively low and in some parts of the island can be in fact negligible (Brereton, 1995). As the supply of pasture is critical to reducing cost and improving milk quality and quantity (Sayers and Mayne, 2001; Dillon *et al*. 2002; Kennedy *et al*. 2007) management strategies need to be in place that enhance the supply of much sought after spring grass.

In terms of the supply of grass in the spring, what happens from a management perspective at the very end of one season can often determine what will happen at the beginning of the next. For example, the decision around the closing date of paddocks in a rotational grazing system in autumn can have the greatest impact on the supply of grass in the following spring (O'Donovan *et al*. 2004). Nonetheless, it has also been found that the application of fertilizer N in spring has an important role to play in increasing the availability of spring grass (Laidlaw *et al*. 2000; O'Donovan *et al*. 2004).

A considered approach must be taken to the application of spring N, one that will maximise the proportion of grazed grass in the diet but that will also take into account the recovery of N applied in grass. The amount of N recovered (ARFN) having a direct bearing on the efficiency of fertilizer N use and on the potential of losses of N to the environment.

Moving forward into the rest of the growing season fertilizer N can be applied to the same area of grassland on up to as many eight to ten occasions per year. If the traditional method of applying fertilizer N one to two days post-harvest is used then this can culminate in fertilizer being spread on up to 85 separate application events over the course of a year on farms (Treacy, 2008). This may have negative consequences on labour efficiency, energy use and hence cost effectiveness (Ferris *et al*. 2008).

In order to tackle these issues and to simplify the recording and operational management of fertilizer application, a "blanket" approach to spreading fertilizer N may be a more viable long term strategy. However, one of the biggest concerns posed by such a strategy is whether or not there is an optimum time within the growth cycle to apply fertilizer N. If there is no particular optimum time, what impact will using a strategy that involves the application of N to grassland at varying stages of re-growth have on overall grass production and plant N uptake?

In order to answer some of these key questions, research work in the present thesis has focused on the type of fertilizer N that should be used, when that fertilizer should initially be applied in spring, what rate of application is required and the effect stage of regrowth at the time of application has on DM yield and ARFN (Brockman, 1974; Murphy, 1977; Stevens *et al*. 1989; Long *et al*. 1991; Laidlaw *et al*. 2000; Watson, 2001; O'Donovan *et al*. 2004; Murphy *et al*. 2013; Antille *et al*. 2015; Forrestal *et al*, 2017). Conclusive answers have been difficult to obtain. This is in part due to annual variations in grass growth and differences between site characteristics but also due to experimental design limitations. This research work aims to overcome some of these previous limitations by broadening the range of application strategies to be examined.

However, this study has its own limitations in that the work is entirely conducted on monoculture perennial ryegrass swards. It does not consider multispecies swards and also excludes the role of legumes such as clover in supplying N and the N supplied by animal manures or soiled water. It also does not consider potential recovery of applied N by the sward post last harvest.

The objectives of these studies were to:

(i) Investigate the impact on grass DM production by application/non-application of fertilizer N in spring and when applying, whether combining two (split) applications of fertilizer N would result in higher grass DM production and greater ARFN compared to a single large application of fertilizer N in spring with specific emphasis on:

(a) determining the effect of single or split N application on grass DM production and ARFN, and
(b) identification of the most appropriate dates for fertilizer N application during the spring.

(ii) Compare the performance of both urea and CAN fertilizers on grass DM production, N uptake and N recovery (study 1 only), when applied at different rates and stages of regrowth over the entire growing season and compare the cost effectiveness in terms of grass DM production.

Chapter 2 Literature Review

2.1 Introduction

In agriculture the harvesting of any crop from the field results in the removal of a portion of the nutrients from the soil. In order for sustainable harvesting to occur there must be adequate replenishment of the soil's "nutrient bank", if not, the result will be the inevitable depletion of soil fertility and the removal of the soil's capacity to grow crops on a continual basis. Apart from the contribution of localised rainfall and the onsite decay of plant and animal material the main method of replacing soil nutrients is through the application of manures and fertilizers.

2.2 Fertilizer use in late 20th and early 21st Centuries

2.2.1 1950's to 1990's

Up until the 1950's only a limited amount of research had been done into the use of N on grassland in Ireland. Some work that had been done by researchers such as J.G Drew and D. Deasey in the late 20's and 30's indicated that there was only modest benefits to be had in relation to the application of N fertilizer to pasture. Following 1945 the Department of Agriculture carried out limited manuring experiments on mainly tillage and root crops as opposed to pasture at the Johnstown castle research institute in Co. Wexford. However, 1958 saw the formation of An Foras Taluntais (became Teagasc in 1988), a semi state body, whose purpose was to further enhance and develop many aspects of scientific research in agriculture. In 1959 the body took over research at Johnstown Castle and opened up a new research facility in Moorepark, Fermoy, Co. Cork focusing on pig and dairy production. As a result the late 1950's, 60's and early 70's brought about the first real period of intensive grassland fertilization research with numerous researchers carrying out investigations into the response of hay and grazing pasture to various types, rates, combinations and patterns of fertilizer application in terms of dry matter (DM) production, the chemical composition of grass, botanical effects, effect on clover, live weight gain, stocking rate, milk production, silage conservation and the residual effects of fertilizer application in soils. Their work had a significant impact at farm level as figures show that fertilizer N use on pastures across Ireland grew from 3.8 kg N/ha in 1965 to 9.5 kg N/ha in 1974 to 29 kg N/ha in 1976; this was a big jump in a decade (Le Clerc, 1978). Another driver of increased usage at the time, especially from 1974 to 1976, was Ireland's entry into the European Union (E.U.) in 1973 or the European Economic Community (E.E.C.) as it was known then, which gave Irish farmers access to European funds and larger markets for their products. It marked the beginning of a decade of great freedom for farmers to expand and intensify especially in terms of milk production where up until the introduction of the dairy quota in 1984 dairy output expanded by 70% or at annual rate of over 5% (O'Grada, 2004). Unfortunately the quota system which originally only was intended to last for a few short years remained until 2015 and greatly restricted the dairy industry over that period.

From 1950 to 1985 the use of N had increased 50 fold (from 6,300 to 328,000 t), P usage more than doubled (from 27,000 to 66,000 t) and K usage had increased 15 fold (from 10,800 to164,000 t) (Murphy and O'Keeffe, 1985). In 1985 N use on pasture averaged 48 kg N/ha. Mainly dry stock systems made up the lower values of fertilizer N use (12 kg N/ha) while dairying accounted for higher N inputs (85 kg N/ha). Calcium Ammonium nitrate (CAN) and urea were the main sources (63%) of fertilizer N along with Sulphate of Ammonia (SOA) which had increased in use due to the increasing awareness of the possibility of sulphur deficiency on light soils. Urea increased in popularity in the early 1980's when an excess on the world market lowered the price below that of ammonium nitrate. In 1983 urea was up to 30% cheaper per kg N. The rates of fertilizer N being used for hay and grass silage were close to recommended levels but rates applied to grazing ground were lower than required. Even though P and K use had risen the amounts used in grassland were insufficient to meet hay and silage requirements and only 43% and 48% of P and K respectively, that was needed for grazing land was being applied. The same period saw a welcome rise in lime use with levels rising from 840,000 t in 1955 to over 1.7 million t in 1984 (Murphy and O'Keeffe, 1985).

From 1985 to 2000 N use continued to rise and reached a peak of 425,000 t in 1999. N use on pasture now averaged 93 kg/ha, almost twice that of the 1980's. However, the trend for higher rates of use being observed on dairy systems as opposed to drystock systems remained the same (Murphy *et al*. 1995). A closer look at N use figures on grassland showed that the picture for N use on hay no longer met requirements as they were only 70% of what was needed; this may be a reflection of the fact that hay was no longer seen as an important forage for the purposes of winter feeding. However, N application rates for silage remained on target and application rates on grazing ground had improved since the 1980's as they were now matching recommended levels. CAN and urea accounted for 58% of total N applied to grassland with high N compounds and

18-6-12 making up the difference. P usage in most instances was now at slightly above recommended levels, averaging at 11 kg/ha, most of which was being used on dairy farms. The mean usage of K was 24 kg/ha, suggesting that K usage on many farms was still below what was actually needed.

2.2.2 2000's to Present

At the beginning of the 21st century 81% of Ireland's agricultural area is devoted to pasture, hay and grass silage (3.6 million ha), 11% to rough grazing (0.5 million ha) and 8% to crops, fruit & horticulture production (0.37 million ha) (DAFM, 2015). The dominant enterprises are cattle and milk production accounting for up to 70% of total output with pigs, cereal and sheep output accounting for 7%, 4% and 4% respectively.

N usage for grassland was increasing in the late 90's but decreased steadily from 1999 to 2008 (Lalor *et al*. 2010). In 2008 mean N usage was 86 kg/ha, similar to what was being used in the early 80's. It was 92% of what was being used in 1995 and if compared to 2003 when mean N usage was 123 kg/ha, a fall of 30% had occurred since 1995. Most of the fertilizer N being used was in dairying as the average used on grazed grassland was 112 kg/ha compared with only 28kg/ha in dry stock systems. N use for hay remained relatively stable over the period but a drop of 16% in N use for silage occurred from 2003 to 2008. From 1995 to 2008 there was a consistent drop in N and P use, falling back to levels of use seen in the 1950's. The overall mean P and K usage by 2008 was 5 and 14 kg/ha respectively. These rates are 55% and 48% lower than those of 11 kg/ha for P and 27 kg/ha seen for K in 2003. The drop in P and K use was seen across the board in terms of hay, silage and grazing ground applications. By 2008 CAN and urea made up 65% of the N supplied to grassland with high N compounds making up the difference. The drop in the use of high P and K compounds in conjunction with the large amount of N being supplied in the form of straights resulted in the relatively larger decrease in the usage of P and K than that of N (Lalor *et al*. 2010).

The main reason for reduced usage was the increasing cost of fertilizers. Others reasons included; declining cow numbers due to quota restrictions, improved utilisation of animal manures, decreasing product prices and farm income, regulation of nutrient usage and the policy of extensification introduced in 1998 (Humphreys *et al*. 2008). From 1995 to 2015 the sale of fertilizers in Ireland fell by 28%, hitting its lowest point in 2009 when it was 41% lower than 1995 levels (Teagasc, 2018). Up until the mid-90's farmers were reluctant to reduce the amount of fertilizers they were using as their use had been economically justifiable due to the value of extra grass produced relative to the cost of fertilizer (Jarvis *et al*. 1996). However, increases from 155 and 201 €/t in 1995 to 322 and 395 €/t for CAN and urea, respectively, marked a rise of almost 123% and 130% for the two most commonly used fertilizers on Irish farms. The price increase was not matched with an increase in farm-gate product price or farm incomes forcing farmers to become more efficient in their use of fertilizers and their utilisation of animal manures if they wanted to remain competitive.

Milk output in Ireland has risen from approximately 2.2 billion litres from less than one million dairy cows in 1960 to 7.5 billion litres from almost 1.4 million dairy cows in 2018 (DAF, 2003; CSO, 2019a; CSO, 2019b). The increase in milking cow numbers and in particular the increase in production per cow from under 2,000 L/cow to in excess of 5,000 L/cow over the period has resulted in huge intensification in production over the last 60 years. This has led to increased and sometimes inappropriate use (excessive amounts and poor timing) of chemical fertilizers which lead to inevitable increased losses to the environment (Hilhorst *et al*. 2001). To counteract concerns in relation to environmental losses nutrient use regulation was introduced. In 1991 the E.U. introduced the Nitrates Directive (Council Directive 91/676/E.E.C.) which forms an integral part of the E.U. Water Framework Directive, 2000 and is implemented currently in Ireland under SI 605 of 2017 (Good Agricultural Practice for the Protection of Waters). These regulations were designed to protect waters from nitrate pollution from agriculture and has led to codes of "Good Agricultural Practices" which set restrictions on the quantities of fertilizer that can be used relative to animal stocking rates.

Lower fertilizer inputs represent cost savings to the farmer, and may indicate more efficient nutrient use on farms and lower environmental losses. In future the maintenance of soil fertility, particularly of P and K are essential to maintain the production capacity of soils. Sales of P and K have risen 24% and 26% respectively between 2009 and 2015 and may indicate awareness of the need to begin refocusing on the importance of P and K as well as N (Teagasc, 2018). However, all this will be futile if the fundamental step of liming is not improved. Our record in relation to lime has always been poor. In the last four decades national lime usage has dropped from 1.7 million t/yr in the 1980's to an average of 725,000 t/yr in the 2000's, levels almost identical to those in 1960. Added to the drop in application rates of lime, our high rainfall means that much of the lime in soils is lost through leaching and water drainage and is not being replaced, the result is that 60% of agricultural soils, again similar to the 1960's, are below the target pH of 6.3 for grassland. As soils provide the nutrient source in grass based systems, focus now on the strategic application of lime, animal manures and of chemical N, P, and K fertilizers is paramount if the ambitious targets of production as set out in Foodwise 2025 are to be met.

2.3 Nitrogen fertilizer use during the spring

2.3.1 Introduction

Local environmental factors, grassland management practices and sward composition are some of the major components in the supply of sufficient quantities of good quality grazing pasture throughout the grazing season. Temperature, incidental solar radiation, day length and rainfall distribution are amongst some of the main environmental influences affecting grass growth and are of most critical importance in grass based systems at the beginning of the grazing season when there is a requirement to reduce silage and concentrate intake. Management practices such as water supply, the rate and type of nitrogen application, its timing and the resting of pastures from grazing all have large effects on the seasonal production of grass in Ireland (Brereton, 1995). In order to optimize animal production while simultaneously maintaining sward quality, pastures need be grazed in early spring (Kennedy *et al*. 2007). To make pasture available in spring significant advancements have been made in plant breeding, resulting in new grass cultivars having a higher spring DM yield potential than previously recommended cultivars (DAFRD, 2002).

2.3.2 Regional patterns of spring growth and grass utilization across Europe and Ireland

Due to a temperate climate Ireland experiences mild winters, cool summers and relatively evenly distributed annual rainfall throughout the year, all of which allow for some level of grass growth all year round. This allows us to achieve strong spring growth of utilizable grass, early turnout dates, high annual DM yields and long grazing seasons. Consistently high levels of grass DM production have been reached, typically ranging from between 13.6 and 15.8 t DM/ha/yr (Humphreys, *et al*. 2004), but in some instances with the use of newer grass varieties, levels in excess of 18 t DM/ha/yr have been attained (DAF, 2004). This compares very favourably with other European regions where at fertilizer N inputs of 300kg N/ha annual yields of only 11-12 t DM/ha are obtained in eastern England and mid to eastern France, 10-11 t DM/ha in the Netherlands and falling to under 10 t DM/ha in Denmark and Germany (Brereton *et al*. 1996). This drop off in DM yield going from west to east across Europe is linked to the drop off in the length of the growing season as you move from >300 days in the southern half of Ireland to 250-300 days in Wales, England, France and the north of Italy to 230 days in the Netherlands and drops further again to 200 days in parts of Germany (Brereton *et al*. 1996). Moving further east to other parts of continental Europe there is significant use of maize silage and imported concentrates and as a result there is little or no grazed grass at all in the animal's diet (Knobbe *et al*. 2006). In terms of the variability of grass production, even though Ireland is a relatively small island in comparison to the vast expanse that is mainland Europe there are regional differences to be seen in terms of annual DM yield, animal turnout date, grazing season length and the quantity of grass grown in the spring.

In the south west of Ireland grass growth continues virtually all year round, falling to 270 days across the midlands and falling further again to 240 days in the Northeast (Collins and Cummins, 1996). The shortened number of growing days in the North east therefore results in typical average annual production figures of only 11 t DM/ha/yr compared with that of 15 t DM/ha/yr in the south. The national trend for turnout date is similar to the trend for total annual yield. Turn out date is earliest in the south at around mid-February, falling back to mid-March across the midlands and progressively later around early to mid-April towards the North east. As a consequence the length of the grazing season is longest in the south (233 days) and is the shortest (205 days) in the North of the country (Lapple *et al*. 2012). Early turnout to grass is not a consideration in many European farming systems as the first harvest tends not to occur until late April to mid-May, whereas in Ireland there is a lot of focus on maximising the use of spring grass, as turnout date as explained above occurs before this point in most parts of Ireland. Over the winter and early spring a certain amount of grass growth does occur and the quantity of which depends on location. Brereton (1995) estimated that mean grass growth rates over a 150-day winter period from the 1st of November to the 31st of March varied from 5 kg DM/ha/day in Northern Ireland to 11 kg DM/ha/day along the south-west coast of Ireland. At Moorepark (south-west of Ireland; Latitude 52° 09' N, Longitude 08° 15' W), average daily grass growth rates of 13.5 kg/ha/day were recorded between the 20th of October and the 18th of March (159 days) over a three year study (O'Donovan *et al*. 2004). Average growth rates of 6.1 kg DM/ha/day at Grange (Latitude 53° 31' N, Longitude 06° 40' W) in the Northeast and 11.9 kg DM/ha/day at Moorepark between the 10th of October and the 20th of February (133 days) were recorded over two winter periods

(Hennessy, 2005). Therefore, daily grass growth rates in Ireland range between 5 and 12 kg DM/ha during the winter period.

2.3.3 Environmental factors influencing growth

The relationship between grassland based animal production and climate throughout the temperate areas of the world is of great significance (Soussana and Lüscher, 2007). Meteorological factors are the main cause of regional variation in yields, whereas variation in soil and sward composition is of relatively less importance (Brereton, 1995). In terms of spring production numerous researchers have cited temperature as being the overriding factor in determining pasture production in the spring (Davies and Morgan, 1988), however other workers have shown that not only temperature but low incidental solar radiation and day length have a major influence on grass growth over the winter and early spring (Brougham, 1959; Strengbom *et al*. 2004). In fact (Brougham, 1959) indicated that there was a stronger correlation between light and growth rate rather than temperature and growth rate. Evidence over twenty years shows that the start of growth in spring varies considerably both within and between regions from year to year with soil temperature at 10cm being a better climatic indicator of when grass growth commences rather than T-sum 200°C (Davies and Morgan, 1988). When soil temperature at 10cm is less than 4.5°C grass growth is virtually zero. Only when soil temperature rises to between 5.5°C and 6.0°C does grass growth begin to accelerate (Parsons and Chapman, 2000). Studies have shown that leaf growth in perennial ryegrass is stimulated at about the time at which the crop becomes vernalised during the winter. Vernalisation is the programmed physiological process in which cold exposure over prolonged periods provides the ability to flower in plants (Xu and Chong, 2018). Low temperature has an inductive effect and floral initiation occurs after returning plants to a higher temperature (Thomas and Vince-Prue, 1996). In relation to light, alterations in day length associated with seasonal changes are amongst the most accurate cues to determine the right times for grasses to flower (Colasanti and Coneva, 2009) having a knock on effect on leaf extension rate for the growth of grass swards in spring. The more rapid extension of leaves of vernalised grass into the upper, less shaded, horizons of the sward results in an enhancement of the photosynthetic potential of the leaves (Woledge, 1979) and thus greater potential for growth. (Cooper, 1960) observed that while most temperate grasses were induced outdoors by the beginning of January, the critical photo-period for flowering varied from about 13 hours to 10-12 hours for late and early varieties, respectively. As to when exactly all the conditions needed to initiate growth are met we need to look at what happens in terms of temperature and light over the late winter and early spring period.

2.3.4 When are the meteorological requirements for grass growth met?

The winter solstice is an astronomical phenomenon marking the shortest day and the longest night of the year. In the northern hemisphere this is the December solstice occurring between the 21 and 23 December and in the southern hemisphere it occurs between the 20 and 21 June. In the northern hemisphere, in the period between mid-September and the winter solstice, the crop is in the unvernalised vegetative state and has a relatively low growth potential (Davies, 1971; Parsons and Robson, 1982; Brereton *et al*. 1985). Up to this point soil temperatures are cooling down but may indeed still be high enough to satisfy conditions for grass growth but day length is shortening and as a result the efficiency of radiation use by the grass plant before mid-winter is only about 40% of the efficiency after mid-winter (Brereton, 1981). After the winter solstice soil temperatures at 100 mm will at some point drop to about 4.5°C and then this is when vernalisation of the grass crop is completed and the crop moves to the reproductive state (Brereton *et al*. 1985). The next step in the process occurs in late winter and early spring when temperature is greater than 5°C and growth potential is significantly increased. Even though growth is possible with ever increasing solar radiation as a result of longer day length, soil temperature is most likely lower than 10°C, meaning that growth is still limited by temperature. As there is a positive correlation between growth rate, light and temperature, during winter and spring months, weekly fluctuations in the growth rate of ryegrass and consequently total grass yield are associated with fluctuations in light and temperature range (Brougham, 1959; Kim *et al*. 2009). The magnitude of these weekly radiation and temperature variations and their positive correlations to grass growth suggest that, under field conditions, the growth rate of pasture responds fairly rapidly to changes in environmental conditions. In essence temperature is acting like a hand-break on growth and it is only when consistently higher soil temperatures are present that there will be prolonged periods of continued grass growth.

2.3.5 Autumn management of pasture for spring production

The autumn management of the sward has a far greater influence on the yield of grass in the early spring than any other factor under the control of the farmer (Murphy, 1977). At this time of year some of the key aspects to management include the length of the grazing rotation, the amount and timing of fertilizer N application and the closing date of paddocks required for early spring grazing. Laidlaw and Maine (2000) indicated that in order to provide sufficient quantities of grass for grazing, rotation length needs to be extended from three to four weeks in late July to approximately eight weeks for paddocks grazed in mid-September to early October. Even though there is considerable flexibility in extending grazing rotation care must be taken not to extend the rotation too far as excessive rotation lengths have a negative effect on grass quality, in particular, green leaf mass. An indication of the maximum length of regrowth interval may be when the contribution to leaf mass by the youngest leaf category is similar to green leaf material older than the first expanded leaf. The response of grass to N fertilizer in autumn is lower than any other time in the growing season, unless there is severe drought over the summer period (Laidlaw *et al*. 2000). In terms of fertilizer application date for autumn production the optimum time for applying fertilizer N appears to be mid to late August. As the response to fertilizer application is low, the rate of fertilizer used needs to be based on stocking rate and on the potential for animals to utilize grass in an extended grazing season. The importance of autumn closing date on DM yield in the following spring has been highlighted in a number of studies (Carton *et al*. 1988; Roche *et al*. 1996; O'Donovan *et al*. 2004). These studies have suggested that a more planned approach to autumn grazing management is required in order to build up a grass “bank” and thus ensure a greater supply of grass in the following spring enhancing the possibility of achieving an earlier turnout date to pasture. Delaying closing date in autumn reduces available grass in the following spring (O’Donovan *et al*. 2002) For each one month delay in closing date, from mid-August to mid-November, there is a significant reduction in total and leaf DM yields in early spring (Carton *et al*. 1988).The importance of closing date however is only relevant where early access to grazing in spring is required. As the time of the first grazing becomes later the influence of closing date fades as its effect is reduced later in the spring and early summer (Davies and Simons, 1979).This allows for greater flexibility in choosing the date of autumn closing on swards not specifically required for early grazing in spring and thus allows for the extension of the grazing season into mid to late November, a practice that has become increasingly popular on dairy farms throughout the areas of the United Kingdom and Ireland which experience mild winters. Where there is a requirement for the early access to pasture in spring, mid-October would seem to be a preferable target for closing date in autumn (Carton *et al*. 1988). In the context of a rotational grazing system where a proportion of the paddocks are not grazed in spring but cut for silage in May the management strategy should be to begin the last grazing cycle in mid-October. The paddocks which are to be grazed first in spring should be closed earliest and those required for grazing later in the spring or required for silage should be closed last, with a total cessation of grazing by the beginning of December (Teagasc, 2011).

2.3.6 Forms of nitrogen fertilizer

Ammonium and nitrate are readily absorbed by plants, and are the dominant sources of N in the soil for plant growth. As a result, the most common forms of inorganic fertilizers used in farming systems contain N either in the form of nitrate-N or ammonium-N or a combination of the two. Today two of the main products used include calcium ammonium nitrate (CAN) and urea.

CAN, also known as nitro-limestone, is widely used, accounting for 4% of all fertilizer use worldwide at the beginning of the last decade (Smil, 2000). CAN is produced in either granular or prilled form, containing 27% nitrogen (13.5% ammonium-N and 13.5% nitrate-N) and has a high lime content (approx. 8%) resulting in its preferred use on acid soils as it acidifies soil less than many other common N fertilizers (FIFA, 2006). The combination of ammonium-N and nitrate-N makes CAN a universal fertilizer, which has the capability to deliver an optimal N supply to all plants. It considerably improves the fertility of the soil, and therefore increases the growth and yield of the plant.

More than 90% of the world urea production is allocated for agricultural use as N fertilizer (Meessen and Petersen, 2004). Urea contains 46% N, all in amide form, which means it has the highest nitrogen content of all solid nitrogenous fertilizers in common use. Urea is produced in either prilled or granular form. In recent years it is mainly produced in granular form as granules have a more uniform size distribution compared with prills, ensuring a more even spread of the product on the field. Also prills have a low impact rating which means much of the product is damaged (crushed to a dust) during high volume storage.

Numerous studies with varying outcomes have been undertaken to examine the efficiency of these different forms of N at the first application with the view to establishing the most appropriate form of N fertilizer for grass growth in relatively cold soils in the early spring. The efficiency of fertilizer N sources has been related to their susceptibility to gaseous loss by denitrification, to ammonia volatilization and to leaching (Herlihy and O'Keeffe, 1987; Ryan *et al*. 2006; Harty *et al*, 2016). Environmental influences including temperature and rainfall, rainfall especially around the time of application have some of the biggest influences on the aforementioned processes and thus on the performance of the different types of inorganic fertilizers (Sanz-Cobena *et al*. 2011).

During the early spring ryegrass will be subject to differential root and shoot temperatures. Watson (1986a) used the ^{15}N isotope to compare the uptake and recovery of ammonium-N and nitrate-N by ryegrass growing in soil under low root and shoot temperatures. The results indicated a preference for the uptake of ammonium-N over nitrate-N, particularly at low soil temperatures. The rate of translocation from the root to the shoot was shown to be lower for nitrate-N than for ammonium-N at root temperatures of between 5°C and 15°C, the difference being greater at the lower temperature. It could be argued that the reduced uptake of nitrate-N may have been due to a reported inhibitory effect of the ammonium ion, however, even when the ions were supplied separately, ammonium was still absorbed by the root more readily. In the same year Watson (1986b) reported on other work using three forms of fertilizer, which aimed to quantify the difference between ammonium and nitrate N forms on DM production and N uptake by ryegrass under wet conditions. The effect of wet spring conditions were simulated using a short term irrigation experiment. All fertilizers significantly increased yield and N uptake compared to no fertilizer application in both irrigation and non-irrigation regimes. When no irrigation was applied there was little difference between fertilizer forms in terms of yield and N uptake. However, when irrigation was introduced, nitrate-N resulted in a significantly lower DM yield and N uptake compared with AS and urea. This may be explained by the fact that NH_4^+ ions are less subject to leaching and denitrification losses compared to nitrate-N, the denitrification of which can lead to substantial gaseous losses of N under wet spring conditions (Ryden, 1982). As a result of the ammonium ions remaining in the soil for longer periods there is greater opportunity for their uptake by the grass sward compared to that of nitrate ions. Also, in theory it is more efficient for the plant to take up ammonium-N, because the plant needs to convert nitrate back to ammonium-N before it can be used in plant metabolism to produce proteins (Hodges, 2002).

Herlihy and O'Keeffe (1987) evaluated and modelled the effect of temperature and rainfall on two sources of inorganic N, namely CAN and urea. In this experiment N was applied either on 17 and 31 January and on 16 and 28 February at a rate of 50 kg N/ha, a level at that time which was consistent with that normally applied to grassland for early grass production in southern Ireland. Two harvests were taken, one at 60 days post application and the second at 40 days following the above harvest (without further application of fertilizer N) to measure residual effects. Temperature and rainfall were measured pre and post each application and harvest date. Simulation studies with the models indicated that, although the influence of temperature was dominant, rainfall modified it strongly in terms of the relative efficiencies of both urea and CAN and the magnitude of the response. Generally there was a trend for somewhat higher yields, N uptakes and responses in the urea treatment compared with CAN. This indicated that the efficiency of urea is better in areas of milder, wetter climate compared with CAN as long term rainfall appears to be more detrimental to nitrate sources. However, it was noted that in dry springs the response to CAN may be comparable to or even surpass that of urea. The residual effect of both CAN and urea was variable but in general terms was higher when the direct effect was low, say in colder springs. Low and high residual effects were associated, respectively, with mild conditions of high rainfall and cold conditions that reduced response and N uptake in the first harvest.

Stevens *et al*. (1989) carried out field plot experiments over a three year period at four sites in Northern Ireland to study the effect of date of application of CAN and urea on perennial ryegrass production in spring. Fertilizer was applied over a ten week period from 1 February until 5 April. Differences in performance between CAN and urea were only significant for three of the 120 fertilizer applications at the first cut. On these occasions, all in one year at two of the sites, urea gave higher yields than CAN. Correlations were examined between DM yield response and growth period, air temperature, long-term rainfall and short-term rainfall for CAN and urea separately. In examining the results one of the significant factors correlated with DM yield response to CAN was rainfall on the day of application and the following two days. CAN exhibited a significant negative correlation with short-term rainfall, while factors relating to rainfall appear to have had no significant effect on DM response to urea.

Swift *et al*. (1988) performed experiments over a three year period in eastern Scotland whereby a single application in spring of aqueous ammonia at a rate of 360 kg N/ha was compared to split applications of ammonium nitrate and urea in terms of seasonal and total annual DM production, grass N content and apparent recovery of fertilizer N. The split application entailed applying fertilizer on five separate occasions throughout the year, i.e. 90 kg N/ha from 2 March to 6 April, 90kg N/ha after a harvest in May and three applications of 60 kg N/ha after each of three harvests (4 to 5 week intervals) until August, 360 kg N/ha total. The performance of a single application of aqueous ammonia was variable but in most instances showed poorer spring and total annual DM production compared with ammonium nitrate following March and April applications. A January application was applied in the first year of the experiment but was discontinued in the following years as it resulted in very poor DM yields, had poor persistency over the season and was deemed too environmentally risky an application particularly on sandy loam soils.

Urea produced 7% less DM in spring than ammonium nitrate. Grass N content and apparent fertilizer N recovery were also lower with urea than with ammonium nitrate. The poorer performance of urea in the spring in this study is in contrast to results shown in Ireland by (Watson, 1986a) and (Murphy, 1983) which showed in comparisons with CAN, prilled urea was as effective in spring but was less effective in summer. Swift *et al*. (1988) had prolonged periods of drought, the lower efficiency of urea may be attributed to loss of N by volatilization to ammonia, a phenomenon found to be prevalent in cold, dry conditions in the spring (Ryden *et al*. 1983). Despite the poorer spring performance of urea this study did show in all three years that urea gave a total annual DM yield within 4% of that given by ammonium nitrate indicating that urea can be used in the spring as a viable alternative taking into account that it must cost 20% less per kg N than ammonium nitrate.

Concerns over urea being more prone to ammonia volatilisation than other N products prompted trials to be carried out in the mid-nineties in New Zealand, where urea is popular and widely used (Harty *et al*. 2016). Craighead *et al*. (1997) compared four fertilizer types, CAN and ammonium sulphate nitrate (ASN), which contain some nitrate-N with urea and ammonium sulphate (AS), which don’t contain nitrate-N. The experiment showed that in general those N products containing some nitrate-N, such as CAN and ASN, could be more effective at producing grass DM than urea and AS when soil temperatures were low. However, grass DM responses were inconsistent because of varying spring climatic conditions. In 1994 and 1996 CAN produced the most grass DM but in 1995, DM responses to the form of N were less clear. In 1995 soil temperature remained at 3°C for three to four weeks. Responses to nitrate-N were generally best when spring soil temperatures were between 3 and 5°C at the time of application. At between 7 and 9°C there was no difference between N fertilizers. Once again urea was less productive than nitrate based fertilizer in colder, dryer, spring conditions. However, similar to the research in Scotland, other New Zealand research has found no difference between urea, ammonium nitrate and AS over the entire growing season (Ball and Field, 1982).

These studies seem to indicate that environmental influences and the cost of fertilizer N have the greatest bearing on whether to use nitrate or ammonium based fertilizers. The conclusions are consistent with the growing awareness that meteorological support data are required in the interpretation of the efficiency of fertilizer N sources and that short-term weather forecast may therefore be another criterion to be considered in deciding when to apply N in early spring. In wet springs and especially around the time of fertilizer application when rainfall is forecast, early spring N should be applied in the ammonium form rather in the nitrate form, as it is less prone to leaching and denitrification and can obtain more efficient utilization and increased DM yield. There appears to be conflicting evidence as to the performance of both fertilizer types in cold spring conditions but in dryer springs and when avoiding rainfall events at time of application, a fertilizer containing nitrate-N could have some advantages. This is because nitrate is the more mobile of the two forms and so less moisture is required for nutrient movement through the soil making it easier for nitrate to be made available to the plant root system.

Cost is the other big factor in choosing a fertilizer. At current fertilizer prices in Ireland (CSO, 2018) (urea = 85 cents/kg N, CAN = 106 cents/kg N) above a growth response to urea relative to ammonium nitrate of 76% it is more cost effective to spread urea, however urea must be used in optimum conditions to make the most of the price differential. As spreading in dry weather makes CAN more reliable and even though urea remains the cheapest source of N, choice of an alternative product may benefit those farmers requiring strategic spring growth, particularly on well maintained (and highly stocked) pasture containing N-responsive grass species.

2.3.7 Application strategies in spring (Date and Rate)

In Ireland dairying is based on the production of milk from grazed grass because grazed grass is a high quality low cost feed and therefore it is desirable to maximise the amount of grazed grass in the animal's diet. One way of doing this is to increase the potential for grazing by extending the grazing period both at the beginning and end of the grazing season as extra grass production is most valuable at these times. This can be done by manipulating the grazing pattern in late autumn and also by the early spring application of fertilizer N which advances by a number of weeks the date on which a yield suitable for grazing is obtained or increases grass yield by a given date (McCarthy and O'Shea, 1986; Stevens *et al*. 1989; Hennessy *et al*. 2006). The choice of date and rate of application of fertilizer N is one which is under the control of the farmer. With regard to date, assuming the land is trafficable, the decision to apply is based primarily on when the grass is required and when it can be utilized. In relation to the rate of N applied, a balance needs to be struck between applying enough fertilizer N to allow the full growth potential of the crop to be realised and yet at the same time not create a situation where there is a build-up of unused N which may be vulnerable to loss either through, leaching, volatilization or de-nitrification. With this in mind, it is reasonable to assume that the splitting of N-dressings in early spring may be a better approach than depending on one single application on any given date in order to maximise grass growth potential and N-use efficiency and at the same time minimise the risk of N-loss. A number of studies have been conducted to ascertain the best possible approach to early spring fertilizer N application.

As the number of grass growing days varies from >300 days in the south west to 240 days in the north east of the country, so too is there variation throughout the country on when the optimum time might be to apply fertilizer N. Murphy (1977) showed that the effect of date of N application on DM yield is significant but that there is considerable variation in the optimum time for applying N for spring growth. However, the work suggested that the optimum date for applying N for early spring grass was sometime in January for Johnstown Castle Research Centre which is based in Co. Wexford in the south east of the country.

Stevens *et al*. (1989) carried out field plot experiments over a three year period at four sites across Northern Ireland to study the effect of date of application of CAN and urea on perennial ryegrass production in spring. A single application at a rate of 70 kg N/ha was applied at weekly intervals over a period of 10 weeks beginning February 1 (when soil temperature at 100mm was >5.5°C) and ending on April 5. All plots were harvested for the first time in late April/early May in all three years. The results indicated a significant ($P < 0.001$) response to fertilizer N and that the date of application for maximum DM yield at the first cut differed with site and year, but for 11 of the 12 site/yr combinations the optimum application date was in February.

Le Clerc (1976) observed that N applied at very high rates in February gave higher yields than split dressings or the same amounts applied later in the year. However, this strategy exposes applied N to greater potential loss to the environment (Ryden, 1984) and is in contrast to other research findings. For example, experiments carried out in North Wyke in England (Brockman, 1966) focused on the effect of the stage of defoliation and single versus split applications of fertilizer N on grass growth in early spring. Results indicated that early defoliation restricted DM response to N but increased its residual value which may have a beneficial effect on regrowth after defoliation. However, this was of no benefit when aiming for early grazing, as it does not allow for a complete response to heavy (90kg N/ha) N applications. Therefore a smaller application (40 kg N/ha) of N prior to grazing followed by another small application post defoliation may be a better strategy in order for the crop to fully utilize fertilizer N and reduce reliance on residual N effects for subsequent growth.

At Moorepark research centre in Co. Cork an experiment was carried out by O'Donovan *et al*. (2004) over three years which examined the effect of winter and spring applications of fertilizer N on grass DM yield, N uptake, N recovery and N efficiency. The winter applications prior to the winter solstice were associated were greater losses of N, probably due to either leaching or denitrification. Application post winter solstice performed better on all parameters measured, with an optimum application date of mid-January for grass required in mid-March and an optimum application date of early February for grass required in early April. The work also concluded that a rate of between 30 and 60 kg N/ha is the most appropriate level to apply, depending both on the demand for early grass and the milk to fertilizer N price ratio.

The general consensus of these studies is that there is considerable variation in the optimum time for applying fertilizer N in late winter and early spring. It appears that seasonal growth can be affected by numerous management factors and further still, even if management strategies were to remain constant year on year, climatic variation leads to variability between years in terms of sward N-uptake (Salette *et al*. 1989). Matching the application of fertilizer N to the start of grass growth in the spring is a precarious strategy as the correlation between the start of spring growth and accumulated soil temperature has been proven to be unreliable (Swift, 1983). The use of soil (>5.5°C) or air temperature (T-sum 200) as predictive systems have also been shown to be no more successful at predicting optimum application date compared to a simple date range. In summary, the decision to apply fertilizer N may be more appropriately based on the awareness of the short term weather forecast, that the use of split applications is preferable in order to reduce the risk of N-loss, that the rate of application should be governed by the growth period expected (Brockman, 1966) and the economic value of applying N.

2.3.8 Sward composition

It is difficult to alter the environmental factors affecting grass growth but attention can be paid to altering the composition of the sward in order to improve productivity at particular times of the year. Since the start of the 1970's recommended lists of perennial ryegrass varieties have been available in Ireland. Initially varieties were only assessed on DM yield and persistency, however due to increasing requirements for improvement in the nutritive value of varieties, increased testing for digestibility and other quality parameters has arisen (Grogan and Gilliland, 2011). As a consequence there has been improvement in grass nutritive value, be it digestibility, reduced secondary heading, increased water soluble carbohydrate concentration, or greater spring and autumn distribution of yield. The presence of diploid ryegrass varieties has dominated the varietal landscape but the use of tetraploid varieties has risen steadily since 1981; from less than 20% in southern Ireland to approximately 40% by 2010 and from less than 10% in Northern Ireland to about 30% by the end of the last decade. Heading date is known to have a strong influence on leaf expansion rate in early spring (Kemp *et al*. 1989), as a result a superior yield in spring for early heading varieties over late heading varieties is to be expected (Davies and Morgan, 1988; Brereton and McGilloway, 1999). The use of such early varieties however has declined dramatically over the last 30 years, mainly due to problems with stemmy regrowth from the early maturing varieties mid-season and also their lack in the persistency in the sward over time (Gilliland *et al*. 2007). Estimates for the increase in total DM yield due to the recommendation of improved varieties over the past number of years are of the order of 0.5% per annum (Van Wijk and Reheul, 1991; Gilliland *et al*. 2007). The increase is mainly due to a combination of the reduction in the ratio of early to medium and late heading varieties present in the sward and the superior DM performance of new varieties which can out yield older varieties by up to two or three times what was being achieved in the past (Wilkins *et al*. 2000).Much of the increase in DM yield from medium and late varieties has been focused in their spring output and as a result has aided the increase in the proportion of grazed grass in the diet of spring calving dairy cows (O’Donovan and Delaby, 2005).

2.4 Nitrogen fertilizer use during the main growing season

2.4.1 Introduction

A key challenge for any grassland based system of production is to consistently maintain a supply of good quality grass that is sufficient to meet the production and maintenance needs of the grazing animal throughout the entire grass growing season. In order to achieve such a goal account must be taken of the animal’s seasonal nutritional requirements, thus allowing targets for grass production to be established which in turn are then met by natural supply and recycling of nutrients within a grazing system. When nature alone cannot meet the desired requirement for nutrients such as N then the strategic use of artificial mineral fertilizers can be used to make up the shortfall (Rathke, *et al*. 2006). The efficient and balanced use of these fertilizers is then best achieved by quantifying the requirement of N in grassland, the amount of N supplied by natural processes and the calculated application of only the required amount of artificially supplied N that both optimises N uptake and avoids unwanted surpluses (Powell *et al*. 2010).

2.4.2 Soil processes

Soil is at the core of the cycling of N in grassland as it acts as the main source of N and provides the medium for the majority of processes that occur which make N available or unavailable for plant uptake. The N that is available in soil is obtained via wet and dry atmospheric deposition, by biological fixation of N, the net mineralisation of soil organic matter (SOM), from imports of mineral N fertilizers and organic manures and through the N excreted in the dung and urine of grazing animals.

The dry deposition of ammonia-N found as absorbed compounds on dust particles and the wet deposition of ammonium-N found in precipitation as dissolved compounds amounts to <10 kg/ha each year in Ireland (Sherwood and Tunney, 1991, Sheppard *et al*. 2011).

Nitrogen fixation is a process in which atmospheric nitrogen (N_2) is converted into ammonia (NH_3). The process occurs naturally in the air by means of lightning but also in the soil where it is carried out by N fixing bacteria, some of which (*Rhizobia*) have formed symbiotic relationships with certain plant species (legumes). All biological nitrogen fixation is done by way of the nitrogenase enzyme produced by the bacteria and acts as a catalyst in the reduction of N_2 to ammonium-N (NH_4). In swards with a high content of leguminous plants such as white clover (*Trifolium repens*), biological fixation can be in the region of 31-34 kg N/ha fixed per t of clover herbage DM (Phelan *et al*. 2012). A certain amount of N is also “fixed” by free living bacteria (*Azospirilla*) in the soil but the quantity produced is particularly small ranging from 0.3 to 5.0 g N/ha/day, as a result their exploitation in agricultural systems is small (Rother *et al*. 1982; Hungria *et al*. 2010).

Mineralisation is a process in soils that involves the decomposition or oxidation of chemical compounds in organic matter into plant-available forms of N, such as ammonium-N. The opposite of mineralisation is immobilisation, which results in the conversion of inorganic compounds to organic compounds which are unavailable to plants. Whether N is mineralised or immobilised depends on the C/N ratio in plant residues (Whitehead, 1995; Holtkamp, 2011). If the C/N ratio of the decomposing material is approximately 30:1 then there is too little N in the plant material to allow the soil microbes to convert all of the Carbon into their cells. The soil microbes therefore will take in soil mineral N to carry out the process which results in mineral N being immobilised which can cause N deficiency in plants growing in the soil. As carbon dioxide is released via decomposition the C/N ratio of the organic matter decreases and the microbial requirement for mineral N also decreases. Once the C:N in decomposing plant material is below 25:1 the process of mineralisation will occur and results in higher soil mineral N levels when decomposition is complete (Haynes, 2005).

Gross mineralisation is the total release of ammonium-N before any immobilisation back into the soil biomass. The difference between gross mineralisation and gross immobilisation is either net mineralisation or net immobilisation. In long term productive grassland soils there tends to be a higher level of gross mineralisation versus immobilisation resulting in overall net mineralisation (Jarvis *et al*. 2000b).

2.4.3 Background net mineralisation of SOM-N

Soil organic matter (SOM) is a component of soil that has accumulated over time and is made up of plant and animal residues at varying stages of decomposition (humification), substances synthesised by soil organisms and soil microorganisms themselves. Its presence in soil is vital to soil processes as it has a beneficial effect on soil function and quality as it leads to improvements in soil structure, soil biodiversity and importantly, the storage and cycling of nutrients which can be made available for plant uptake (Baldock and Nelson, 2000; Haynes, 2005). The main source of SOM comes from vegetation which was once growing in the soil, has died and has then undergone decay through the actions of soil microorganisms. The main constituents of the plant residues include carbon, oxygen and hydrogen but they also include other elements vital to plant growth including nitrogen.

The concentration of SOM found in soils varies greatly, ranging from 1% in topsoil associated with desert areas to up to 90% in lowland wet areas (Troeh and Thompson, 2005). Soils containing a minimum of 12-18% SOM are deemed to be organic soils.

In soils used for agriculture large reserves (5000-7000 kg N/ha) of N are found in the SOM, of which on average 185 kg/ha/yr can be made available (Ryan, 1976; Mengel, 1996) and thus makes a large contribution as background N to the growth of agricultural crops through the net mineralisation of SOM. In the top 15 cm of soils in the UK there can be between 1to 4 t N/ha under arable cropping systems and between 3 to10 t N/ha in grassland soils (Archer, 1988, Bardgett and Chan, 1999). The reason that more SOM-N may be found in grasslands soils in contrast to arable soils is due to the fact that continued ploughing of soil in arable systems increases the exposure of SOM to the process of mineralisation which decreases organic N levels in the soil over time. On the other hand, in grassland systems, turnover of the topsoil is far less frequent which protects the SOM and allows for the greater build-up of SOM over time, therefore older pastures can contain large amounts of organic N.

The reserve of SOM-N in agricultural soils has been proven to be high but it is the rate and pattern of release of this mineral N to the growing crop is what is of greatest importance (Gill *et al*. 1995). The humification process is controlled by microbial activity and therefore the factors that influence microorganisms have a knock on effect on the rate of decay of material. These main factors include temperature, soil water content, nutrient availability and the structure of colloidal mineral materials (Haynes, 2005). Data from grass growth measurements taken over a number of years at Moorepark research centre show the quantity of N required for grass growth throughout the year (Humphreys *et al*. 2003b). Average annual grass growth was 15.5 t/ha/yr with a total release of N from the SOM being 140 kg/ha/yr. Assuming an approximate requirement of 30 kg N for every t of grass DM grown then 465 kg N were needed to reach observed yields. This means that over 31% of the crops needs were met by the release of SOM-N. The pattern of release of N from SOM was characterised by peaks of supply in April and August when soil temperature and soil moisture were optimal. Supply was at its lowest during periods of low soil temperatures as those experienced in winter and spring and during periods of lower soil moisture content during the summer months.

2.4.4 High requirement for fertilizer N in grassland

Brereton (1995) indicated that growth rates in winter and early spring (October 1 – March 30) in Ireland varied from 5 kg DM /ha/day in the north to 11 kg DM/ha/day in the extreme south west of the country. This equates to the total potential grass growth over the period ranging from 750 to 1650 kg DM/ha. In order to reach the upper level of this potential yield almost 50 kg N/ha is required. A contribution from the background release of N of 42 kg N/ha over the period as measured in Moorepark would indicate that the release of SOM-N over the period is sufficient to meet the growth requirements of pasture in all instances with the exception of the extreme south of the country (Brereton, 1995). In milder winters O'Donovan *et al*. (2004) recorded growth rates in excess of 18 kg/ha/day which ultimately require approximately 75 kg N/ha to be supplied from the soil. These growth rates cannot be met by background supply of N alone and so there would be a need to supply additional N in the form of mineral fertilizer. An application of 30 kg N/ha (Humphreys *et al*. 2006) in spring would strike a balance between meeting the requirements of the crop and at the same time minimising the risk of loss of N if poor growth conditions were to arise following application.

In Ireland most of the fertilizer N being applied occurs from the middle of spring through to the early part of the summer (Hennessy *et al*. 2008). The reason for this is that background supply of N is unable to meet the N requirements for grass growth. This period can see a rise in grass growth from approximately 20 kg DM/ha/day in mid-March to 80 kg DM/ha/day in mid-April to in excess of 100 kg DM/ha/day in May and early June.

A number of workers both historically and in more recent times (Hunt, 1973; Wilman *et al*. 1977; Bartholomew and Chestnutt, 1978; Vellinga *et al*. 2010; Murphy *et al*. 2013) all indicated that longer intervals between harvests allows for greater opportunity for the uptake and plant utilization of N and thus lead to increased DM production via an increase in the number of tillers produced and larger leaf size being obtained. This poses no issue when N is applied on swards intended for harvest for silage where the growth interval can be between 8-10 weeks but the same is not true in swards that are part of a rotational grazing system where intervals between harvests can be as low as three weeks in the May/June period. However rotational systems do allow for greater flexibility in the size and frequency of N applications (Hunt, 1973; Murphy *et al*. 2013) and also more frequent defoliation improves the ratio of leaf to stem in the sward which improves herbage digestibility (Bartholomew and Chestnutt, 1978).

Hennessy *et al*. (2008) looked at the potential for extending the grazing season by examining the effect on grass growth when the greater proportion of fertilizer N was applied in the spring versus the greater proportion being applied in summer and autumn. At the annual fertilizer level of 250 kg N/ha there was no significant difference in annual DM yield between the two application strategies. However in the absence of applications in April and May in the late application strategy, a significant reduction in DM yield was observed. Humphreys *et al*. (2002a) indicated that fertilizer N applications during the April/June period need to be in the range of 55 to 60kg N/ha applied at four week intervals in order to meet the requirements for grass growth. The N applied will have both an immediate effect on growth but will also have a residual effect as what N is not used for growth in this period will be at a reduced risk of loss to the environment and therefore will remain in in the soil and available for use later in the growing season.

From mid-summer towards the end of the growing season grass growth rates tend to decrease and consequently fertilizer N application rates drop back to beginning of the growing season levels (Vellinga *et al*. 2004). In fact growth rates can now be lower than they were in the spring due to a number of factors including, the plant being in a vegetative rather than reproductive phase, greater competition for nutrients and shortening days resulting in higher rates of senescence relative to new tissue production (Parsons and Chapman, 2000).

The August/September period also coincides with the second peak of release of SOM-N (O'Connell, 2005). This source of N combined with the residual mineral-N that has built up as a result of prior applications during the growing season (Murphy *et al*. 2013) means that N already available in the soil can meet much of the crop's requirements for N. As a result additional N supplied by mineral fertilizer need only be approximately 17-38 kg N/ha in August/September depending on stocking rate (Teagasc, 2017). Higher levels of 50 kg N/ha in Autumn as suggested by (Hennessy *et al*. 2008) may be inadvisable as the possible failure of uptake of such high level of N may result in greater losses of N to the environment over the winter period (Bartholomew and Chestnutt, 1977).

2.4.5 Recycling of N under grazing

N that is ingested by the grazing animal and not turned into meat or milk is returned to pasture through the excretion of dung and urine and by the application of slurries stored over the winter housing period. N can also be returned to the soil through plant senescence.

In swards that are harvested via mechanical cutting recovery of N supplied by mineral fertilizers and fixation can be in the region of 55 to 80% (Ball and Ryden, 1984) and losses to the environment amount to only 10 to15%. Dairy and beef cattle excrete up to 75 to 95% of N ingested resulting in only 5 to 25% of N input being recovered in meat and milk (Whitehead, 1995). Therefore the high rates of recovery seen under cutting are not seen when grazing by cattle is introduced as utilization of N by ruminants is quiet poor, resulting in inefficient N cycling in grassland as most N deposited by grazing is lost.

The proportion of N in either dung or urine varies according to the amount of N in the diet, with high N levels resulting in a greater portion of N being found in the urine fraction (Vertregt and Rutgers, 1987). This has consequences on loss as N in dung is usually in an organic and immobile form whilst N in urine is mainly in urea form, which can be quickly hydrolysed (within 24 hours) resulting in the non-recovery of up to 45% of N deposited in urine through losses via volatilization, leaching and nitrification and denitrification (Vertregt and Rutgers, 1987; Koops *et al*. 1997). In fact even higher losses of N of up to 70% through volatilisation alone have been reported in periods of dry weather. Higher rates of mineral fertilizer N application lead to greater N concentrations in herbage. As a result the amount of N being recycled is lowered as ammonia emissions from grazing tend to increase with increasing rate of fertilizer N application (Watson, 2001) with a linear relationship between increased ammonia loss and increased fertilizer N input (Misselbrook *et al*. 2000).

Animal excreta may recycle between 150 and 300 kg N/ha/yr but the problem is that it is very unevenly distributed (Whitehead, 1986; Dennis *et al*. 2013). Urine is deposited over a relatively small area during urination and the proportion of the grazing area that has urine deposited on it over the entire grazing season is relatively low, typically 0.35m^2 per urination and 21% grazed area coverage over the course of a year (Whitehead, 2000; Dennis *et al*. 2013). This results in concentrations of N in urine deposition ranging from 30-100 g/m^2 or 300 – 1000 kg N/ha which is far greater than plant requirements are at any one time and where levels of C in the soil are only ever sufficient to allow for more modest levels of immobilisation of N to occur (Ball and Ryden, 1984, Haynes, 2005).

Cattle slurries have an important role in the recycling of N in the grassland system, the contribution of which relying on their composition, date and method of application. The quantity of N in slurry varies depending on factors such as animal diet, how long the material has been stored for and whether or not the slurry has undergone any form of treatment during storage, such as aeration. Typical values of N content in cattle slurry are in the region of 5 kg N/m^3 (Coulter and Lalor, 2008).The N is in two forms, ammonium–N which is available for immediate uptake and organic–N which can be taken up more slowly over time. Focusing on the proportion which is more readily available for uptake, most recent work has shown that the best method for optimising N use and reducing losses is by application in spring where immediate N uptake by plants can be up to 30% of the total N in slurry versus only half that in summer and autumn (Matsunaka *et al*. 2006). Slurry injection as opposed to surface application can reduce losses of N via volatilisation by up to 95% (Carozzi *et al*. 2013) and thus further increase the amount of N which can be taken up by the growing plant.

Plant material that is not harvested by the grazing animal can act as a source of N for the production of new plant tissue in the next growth phase. How efficiently animals graze the pasture influences the quantity of that N reserve in undefoliated material. Under good grassland management post grazing sward heights can be between 30 and 60mm representing a grazing efficiency somewhere in the range of 50-75% (Humphreys *et al*. 2003b, Humphreys, 2004). This can result in up to 4 t of DM in total crop yields of 15 t DM/ha/yr that is not harvested for new growth and when it dies off releasing N.
The amount of N recycled in this manner greatly depends on the level of action of soil fauna such as earthworms in the early stages of decomposition and the rate of microbial activity on further decomposition thereafter.

2.4.6 Farm N balance

Nutrient balances are used to represent nutrient flows and provide a useful tool to help understand nutrient use efficiency within farming systems (Bassanino *et al*. 2007). Soil surface nutrient balances (at the crop scale) and a whole farm nutrient balance (quantifying whole farm inputs and outputs) are the two most commonly used balances, however the use of the latter is more favoured as they are more easily and accurately constructed (Oenema *et al*. 2003; Mihailescu *et al*. 2015). In terms of N, a whole farm balance is comprised of the summing of N inputs and N outputs and the difference between the two indicate either a surplus or deficit of N in the farming system. In addition to atmospheric deposition, net mineralisation and fixation of N by clover, the main N inputs include imported mineral fertilizer, feed and organic manures. The main outputs of N include meat and milk production and the exporting of crops and organic manure (Oenema and Pol-van Dasselaar, 1999; Aarts, 2003).
In intensive dairy systems in Ireland yielding 15 t DM/ha/yr or more of grass, mineral fertilizer N is probably the most critically important of all the N inputs brought onto farms as it fills the shortfall between what can be supplied by background N and N-fixation by clover (if present) and what is needed by the growing crop. As most farm N balances result in a surplus rather than a deficit of N in the farming system (Ledgard *et al*. 1997) there is potential for this surplus N from agriculture to contribute significantly to losses to air and water (Toner, 2005). It is therefore important that what mineral N is imported is used as efficiently as possible in order to reduce N surpluses and subsequent potential losses of N to the environment. A number of studies in Ireland have examined the link between surpluses of N in farming systems, the use of mineral N fertilizers and the effect

on output of N and losses to water and the atmosphere (Treacy *et al*. 2008; Burchill *et al*. 2014; Mihailescu *et al*. 2015).

Mihailescu *et al*. (2015) evaluated farm-gate N balances on 21 intensive spring calving dairy farms in the southwest of Ireland between 2009 and 2011. Mean stocking rate was 2.06 LU/ha with mean fertilizer N inputs of 186 kg N/ha and mean N surpluses of 175 kg N/ha across the experimental period. Output was dominated by milk (40.2 kg N/ha) and meat (12.8 kg N/ha) with nutrient use efficiency (NUE) in the region of 23%. Fertilizer N accounted for >85% of all N imports. Higher stocking rates were associated with higher fertilizer N use and higher N surpluses. These results compare favourably with other European studies where mean N surpluses were reported to be 224 kg N/ha. In particular in comparison with Treacy *et al*. (2008) where the NUE at the beginning of a trial on the same intensive dairy farms was 18% in 2003 has now risen to 23%. Much of the improvement was due to decreased fertilizer N input and improvements in N management through the replacement of fertilizer N with on-farm manure in early spring and first cut silage applications. As milk output was maintained as NUE increased, there is evidence to suggest that it is possible to improve both environmental and economic sustainability of dairy production through improved resource use efficiencies.

Burchill *et al.* (2016) measured the N entering and exiting a grass/clover pasture based dairy system over a two year period (2011 and 2012) at Solohead research farm in southern Ireland. Stocking rate was 2.25 LU/ha in 2011 and 2.35 LU/ha in 2012.Averaged over the two years, the system N balance was close to equality as the total N entering and exiting the system was 245 kg N/ha and 269 kg N/ha, respectively. Fertilizer N and biological nitrogen fixation were the main contributors to N entering the system. N output was comprised of milk and meat, which accounted for 79 kg N/ha of N exiting the farm while the remaining 190 kg N/ha exited the farm as losses of N to the environment. NUE in this system was high being 29% in 2011 and 37% in 2012. Much of the loss (43.7%) of N was reported to be in the form of environmentally benign N_2. However, other losses were via leaching, denitrification and volatilisation which were 6.1, 8 and 41.6% respectively and highlight the need for remediation of such losses from such systems of dairy production.

Other studies (Mounsey *et al*. 1998; Humphreys *et al*. 2003a) reported levels of annual N surpluses across a number of intensive Irish dairy farms averaging 262-304 kg N/ha/yr in both studies with fertilizer N accounting for up to 90% of N imports. The construction of farm N balances have now proved crucial as they allow for the quantification of the contribution of fertilizer N to overall N surpluses and creates awareness amongst farmers of the flow of N within their farming systems (Schröder *et al*. 2003). N balances can therefore be used to alter N management on farms and highlights where appropriate quantities of fertilizer N should be used which will result in reduced input costs and can lessen the magnitude of losses to the environment.

2.4.7 Blanket spreading of fertilizer (Pros and cons)

In rotational grazing systems in Ireland the recommendation traditionally has been to apply fertilizer N within one or two days after grazing individual paddocks. This frequency of application equates to fertilizer having to be applied by the farmer on up to eighty five occasions per year (Humphreys *et al*. 2006). As fertilizer N application creates a demand on on-farm labour and energy inputs, the frequency of application is directly related to the cost-effectiveness and practicalities of grassland management (Ferris *et al*. 2008; Dillon, 2017).

Ferris *et al*. (2008) conducted two experiments in Northern Ireland that involved the application of fertilizer either (i) three times (frequent) per week 2-3 days post grazing or (ii) only on one occasion (infrequent) to all the paddocks during the grazing cycle. Two application rates of 250 and 360 kg N/ha/yr were used.

The two N application strategies (frequent and infrequent) being compared in the latter study represent the typical approach of applying N shortly after a grazing event in a rotational grazing system with what has been a more unconventional approach whereby N is applied only once, within a rotation, to the entire grazing platform. The latter approach represents what is known as a ‘blanket’ approach to fertilizer N application and has a number of associated advantages and disadvantages.

The most notable advantage of blanket application is that fertilizer is applied less frequently e.g. only eight times per year, which is in contrast to the eighty five application occasions that can arise in the frequent system (Treacy, 2008). In terms of the actual time spent applying fertilizer Ferris *et al*. (2008) extrapolated that in a 100 cow dairy herd scenario there would be little difference (24.1 mins/wk) in the amount of time saved by the farmer by moving to the blanket application strategy. However, the blanket application strategy allows for the allocation of all time spent applying fertilizer sporadically within a month into one single application event which then creates the potential for the fertilizer to be spread by external labour such as a hired contractor. This would be potentially beneficial as it would result in 7.2 h/mth of a reduction in on-farm labour requirements.

As fertilizer N makes up the largest proportion of N inputs in grass-based systems in Ireland great care must be taken in relation to the accuracy of the data collected by the farmer (Mulier *et al*. 2003) and that biases and errors need to be minimised in order to improve the accuracy of recording N flows through the system (Oenema *et al*. 2003). Higher frequency of fertilizer spreader loadings and varying paddock sizes lead to inevitable excesses of fertilizer N being applied. Blanket application enables more targeted application and improved fertilizer usage which results in a lowering of N input and a follow on reduction in farm N surpluses (Mihailescu *et al*. 2015).

In terms of potential disadvantages, long held concerns in relation to the use of a blanket application strategy mainly revolve around whether or not applying fertilizer N in this manner will have a negative impact on overall DM yield, N concentration in grass DM and increased loss of N to the environment (Sprague and Sullivan, 1953; McKee *et al.* 1967; Brockman, 1974). One important question is whether there exists an optimum stage of regrowth (SOR) for N application within a grazing cycle in order to optimise grass DM production while also controlling N concentration in grass DM and reducing N losses to the environment. If an optimum time does exist, when is it? Is it shortly after harvest or at some other point during the following interval of re-growth?

With blanket application fertilizer N is applied to swards at varying stages of regrowth. Brockman (1974) indicated that N should be applied within one week post grazing if optimal responses in DM yield to fertilizer N application were to be achieved. This suggests that there is an optimal time to apply fertilizer N to grass, which is shortly after harvest and that a more frequent N application strategy may be more conducive to optimising grass DM yield.

The grass that is grown in a pasture based dairy system is fed to animals mainly for the purpose of milk production. Ferris *et al*. (2008) did not directly measure grass DM yield as a result of frequent or infrequent application, (described above) but did calculate daily dry matter intakes of grass to be 13.2 and 13.1 kg/cow, respectively in one experiment and 13.7 and 13.3 kg/cow, respectively in a following experiment ($P>0.05$). As a consequence, treatment had no significant effect in either experiment in terms of total milk output per cow or average daily milk yield per cow.

Treacy (2008) observed that on a study of twenty one intensive dairy farms in Ireland over four years (2003-2006) only one farm in only one year of the study applied fertilizer on eighty six occasions, or 2-3 times per week. The mean number of occasions per year that fertilizer N was applied within the group across the four year period was thirty eight times per year, representing applications of approximately once per week. It is therefore debateable whether or not the high frequency of application required for optimal DM yield is actually really happening at farm level. If this is the case then a change in grass DM production by switching to blanket application may not materialize.

Another potential concern is whether a blanket application of fertilizer may result in changes in the chemical composition of grass resulting in animals consuming herbage that have elevated levels of N concentration. This may have knock on effects in relation to N use efficiency, animal health and potential increase of N loss to the environment

Immediately following the application of N fertilizer there is a rapid uptake of N by grass with crude protein (CP) concentration reaching its maximum level fourteen days after N application and decreases from then on (Murphy *et al*. 2013). The rate of N uptake also increases even more rapidly with higher levels of fertilizer N, with high rates of >60-70 kg N/ha resulting in nitrate-N accumulation as soon as fertilizer is applied (Thomason *et al*. 2004) and thus increasing the risk of reaching nitrate-N levels that are harmful to ruminants and at the same time reducing the proportion of N available for the formation of protein which may affect the swards nutritive value.

Ferris et al. (2008) found little difference in the chemical composition of herbage between frequent and infrequent strategies and showed that an increase in fertilizer rate rather than fertilizer N strategy had greater impact on N concentration in herbage. Fertilizer strategy was also found to have no ill effect on animal health.

Murphy *et al.* (2013) conducted an experiment at two sites in the south of Ireland examining the effect of the carryover of N from one N application (25-50 kg N/ha) to the following growth interval. Grass was harvested from plots four weeks after N application. The grass in each plot was allowed to regrow without any additional N application and was harvested four weeks later. Grass growth and N uptake were measured for both the initial and subsequent four week growing periods and were compared to plots that received no fertilizer N application. DM yield, N concentration and N uptake were higher in fertilized than unfertilized plots and also varied with N application rate. Of the total amount of fertilizer N to be applied that was recovered, 73% was in the initial four weeks and 23% was in the subsequent four weeks. Most (69%) of grass DM yield response to applied N occurred in the first four weeks. Application rates at any one time in this experiment are in line with modern day recommended application rates for grazing swards and never exceeded 50 kg N/ha, much lower than the 60 to 70 kg N/ha associated with nitrate-N accumulation as soon as fertilizer N is applied. This resulted in N concentrations that would also have no detrimental effect on animal health or output performance.

Hennessy *et al*. (2008) conducted two experiments involving the harvest of grass either by grazing or mechanical means and examined the effect of varying fertilizer N application patterns and rates (50 to 250 kg N/ha/yr) on grass production. Similar to Ferris *et al*. (2008) the results indicate that increasing the rate of fertilizer applied rather than the growth stage at which fertilizer N is applied has a greater effect on N concentration in grass DM.

One final area of concern in relation to fertilizer application just prior to grazing is the potential for ingestion by the grazing animal of as yet undissolved granules of fertilizer which lay in the grass canopy or on the soil surface. With the exception of an incident in the early 1980's where the method of fertilizer application rather than the timing of application was the cause of the problem (Horner, 1982) fears relating to ingestion through grazing are unfounded. The literature indicates that direct contamination of drinking water to levels high enough to cause toxicity has been the sole avenue for the poisoning of animals by inorganic fertilizers (Caldow and Wain, 1991; Campagnolo *et al*. 2002; Villar *et al*. 2003). However due care in the application of fertilizer should always be taken regardless of whether a blanket or immediate post grazing application strategy is used.

2.4.8 Apparent recovery of fertilizer nitrogen (ARFN)

In some instances not all of the fertilizer N that is applied is taken up by the growing crop. The applied N that is not recovered by the harvested parts of grass is either immobilised in roots or SOM, contained within stubble or is lost by leaching, ammonia volatilisation and denitrification (Sebilo, et al. 2013; Burchill *et al*. 2014, Burchill et al. 2016) the latter losses representing an economic cost to the user and an increased potential pollution threat to the surrounding environment. The aim of any good fertilizer strategy therefore should be to minimise loss and to maximise the effect that applied fertilizer N can have on grass growth.

The fertilizer N that is taken up by the crop represents an "apparent recovery" (ARFN) of applied N. The amount of N in the crop and percentage ANR can be measured either by using an isotopic method, usually using 15 N-labelled fertilizer or by non-isotopic methods such as the "difference method". ARFN can be described as the amount of N in the herbage of a fertilized sward minus the amount of N in a similar unfertilized sward. It can then be expressed as a percentage of the amount of fertilizer N applied (Burchill *et* *al*. 2014).The response of grassland swards to fertilizer N is not easily explained because the amount of fertilizer N recovered is the net result of the interaction of several key management, climatic, soil and plant processes, the importance of each varying significantly depending on circumstances resulting in ANR which can vary widely, (Humphreys *et al*. 2002a; Burchill *et al*. 2016).

Poor management of fertilizer N results in low ANR. This usually happens when inappropriate fertilizer types are used, applications are poorly timed and/or are applied at a rate that is greater than the capacity of the sward to take applied N up from the soil (Humphreys *et al*. 2003c). The choice of fertilizer type at particular time is of importance in optimising ANR. Applying nitrate based fertilizers in wet springs and in advance of forecasted heavy rains can result in poor ANR, in this case ammonium based fertilizers would be a better choice (Watson and Adams, 1986). In contrast during periods of drying conditions especially over the summer months nitrate based fertilizers may be a better choice due to the increased risk of volatilisation from ammonium fertilizers (Humphreys *et al*. 2003c).

When fertilizer is applied too early, such as in the spring and too late in the autumn, poor rates of ANR can be anticipated. O'Donovan *et al*. (2004) conducted experiments on the effect of late autumn, winter and early spring application of fertilizer N. Results showed that application date had a significant ($P<0.001$) effect on ANR. The lowest rates of recovery in March and April were seen in applications made in mid-October and mid-November being around only 20%. Recovery improved in December and mid-January applications but still only ranged from 23 to 61%. February application resulted in ANR's ranging from 36 to 64%.

Excessive rates of fertilizer application at any time throughout the growing season will result in poor recovery rates. This occurs when more fertilizer is applied than is needed by the crop in the subsequent growth period (Murphy *et al*. 2013). Fertilizer N needs to be applied when the background supply of N is not sufficient to meet the needs of the growing crop, which usually occurs in intensive grazing systems from early March until mid-October. During this period fertilizer N requirements for growth may range from 0.5 to 4 kg N/ha/day (Humphreys *et al*. 2003c). Therefore applications of 30-60 kg N/ha at 4-6 week intervals are sufficient to meet crop needs and ensure high ANR (Murphy *et al*. 2013). In terms of overall annual N application rate, N uptake increases linearly with increasing level of fertilizer N while ANR remains constant up to the point where supply exceeds demand. Greatest recovery is obtained at around 300 kg N/ha/yr, beyond this point ANR falls away as N uptake remains constant (Morrison *et al*. 1980; Greenwood *et al*. 1989; Forrestal *et al*. 2017).

A number of studies have highlighted the effect of climate and soil on ANR in crops. (Pilbeam, 1995) used 15 N-labelled fertilizer to examine the fate of applied fertilizer N in different climatic regions throughout the world, which were ranked according to their precipitation-evaporation quotient by measuring long term levels of precipitation and potential evaporation rates. Results indicated a clear trend whereby climate had a major influence on the amount of fertilizer N taken up by the crop. Higher levels of ANR of 15 N-Labelled fertilizer were observed in the growing crop rather than in the soil in more humid climates. In dryer climates more 15 N-labelled fertilizer was found in the soil rather than the crop, the majority of which, being found in the top 300mm of soil. This underpins the importance of the availability of soil water to facilitate the movement of N (nitrate and ammonium ions) from the soil into roots and further translocation into leaf and stem plant tissue.

Morrison *et al*. (1980) carried out an extensive report across twenty one sites throughout England and Wales on the effect of varying climate and soil conditions at each site on the response of perennial ryegrass to fertilizer N. Results indicated that there were significant differences in DM yield and ANR between sites and that the two most identifiable factors influencing yield and ANR were rainfall amount and soil properties, in particular the soil available water capacity.

The recovery of fertilizer N, particularly at a rate of 300 kg N/ha which was identified as the point nearest maximum recovery and most strongly correlated (R^2 = 0.61) to soil and water factors, was directly related to optimum yield with mean values of ANR across sites ranging from 51 to 87%.

Sites with higher available water capacity (150mm) and highest rainfall (500mm) tended to exhibit highest rates of ANR and higher optimum yields (12.8 t DM/ha). In dryer sandier soils with lower available soil water, evenly distributed rainfall was able to increase rates of ANR (R^2 = 0.57) especially in the mid to late growth period.

The supply of N from sources other than fertilizer N significantly affect the required rate of fertilizer N application (Haynes, 2005), therefore a knowledge of the residual soil N, rate and amount of N mineralised from SOM in the root zone and individual crop requirements are needed to improve the precision fertilizer N recommendations. Humphreys *et al*. (2002b) tabled results on the recovery of applied fertilizer N at two research sites in Ireland. One was in Solohead, Co. Tipperary with a background supply of N of 110 kg N/ha/yr and the other in Grange, Co. Meath with a background supply of 328 kg N/ha/yr. Fertilizer N application in Solohead of 350 kg N/ha on plot experiments averaged yields of 12.2 t DM/ha. Soil in Grange soil can supply three times the level of background N compared to Solohead. Therefore, only a rate of 90 kg N/ha is required to obtain exactly the same DM yield (assuming 84% ANR at both sites). In essence such knowledge has the capacity to prevent excessive rates of fertilizer N being used and that when sensible application of fertilizer is practiced, high ANR between 74 and 86% as recorded in these experiments can be achieved.

2.5 Losses of Nitrogen from Grassland based Dairy Systems

2.5.1 Introduction

Grassland based systems of production are "Leaky" by nature in terms of N loss (Selbie, *et al.* 2015) as less than 30% of N applied is recovered in meat and milk products (Treacy *et al*. 2008; Mihailescu *et al*. 2014; Burchill *et al*. 2016). Well timed and appropriate rates of fertilizer N application result in the majority of fertilizer applied N being taken up by the sward (Humphreys *et al*. 2002a) but when losses do occur there are three major pathways by which losses of N can arise, namely either by volatilisation and denitrification to air or leaching of N to water.

2.5.2 Volatilisation of Ammonium

Volatilisation occurs when ammonium dissolved in soiled water, animal slurry and urine is converted into ammonia gas and is then released and lost to the atmosphere. In grassland systems the emissions associated with the housing of livestock and the storage and spreading of manure are the largest source of ammonia volatilisation (Hyde *et al*. 2003). However, the deposition of dung and urine by the grazing animal and the application of urea containing fertilizers also act as important potential sources of ammonium that can be may be volatilised if not taken up by plant roots (Harty *et al*. 2016; Burchill *et al*. 2017). The process occurs, particularly in dry conditions, within a short number of days following the application/deposition of ammonium laden material to the land. When released the ammonia gas can be carried off by the prevailing winds. It can then be reconverted into ammonium form resulting in elevated ammoniacal N levels in the atmosphere which when deposited in rainfall can lead to soil acidification (Pearson and Stewart, 1993) and eutrophication of water courses (Erisman and Draaijers, 1995; Selbie *et al*. 2015).

In Ireland agriculture is responsible for virtually all (98%) emissions of ammonia (Lanigan, 2017) with an estimated 108.9 kt NH_3-N/yr being produced in 2010. The level of emission is determined largely by the cattle population, resulting in peak levels of emissions, 122.7 kt NH_3-N/yr, arising in 1998 after which there was a decline in animal numbers and mineral N fertilizer use, resulting in 2013 emissions of ammonia gas amounting to 107.8 kt NH_3-N/yr which is 0.4% less than 1990 levels and is 7% below national ceiling emission level which is set at 116 kt NH_3-N/yr (EPA, 2015). However, with increasing meat and milk production since the abolition of the milk quota making it harder to meet future emission targets, a task made even more difficult by the fact that Ireland has committed to reducing ammonia emission levels by another 5% by 2030 (Hennessy, 2016).

It is estimated that mineral N fertilizers account for 12% of ammonia emissions in Ireland and that 2% of the N contained in fertilizers is lost to the atmosphere as ammonia gas (EPA, 2015). As urea is completely comprised of ammonium compared to CAN where only 50% of the N contained is in ammonium form, urea tends to have higher ammonia emissions compared to CAN (Chambers and Dampney, 2009, Forrestal *et al*. 2016). Burchill *et al*. (2016) indicated that when urea alone was used on a grazing system in Ireland it accounted for 41% of overall losses of N from the system via ammonia volatilisation. A study in the United Kingdom (UK) also indicated that losses from urea were greater than they were from nitrate based fertilizers and that losses on grassland soils tend to be higher than they are on arable soils (Chambers and Dampney, 2009). Losses of applied N in the form of urea amounted to 27% (range 10-58%) on grassland experiments and 22% (range 2-43%) on arable experiments. Losses from ammonium nitrate based fertilizers in the same experiments averaged only 3%. This increased loss of N via volatilisation from urea may therefore contribute to observations of reduced DM yield performance in grasslands particularly over the summer period in comparison with CAN (Forrestal *et al.* 2016, Harty *et al*. 2016). Volatilisation losses tend to be highest when urea is applied to soils with a high pH (Nyord *et al*. 2008) with a tenfold increase in volatilisation with every unit of soil pH above 6.0 (Follett, 2001) and in periods where there is high rates of evaporation as found when the weather is warm, dry, sunny and windy (Pain *et al*. 1998). As a consequence the use of urea has been confined predominantly for use in the spring with a recommendation for it not to be used from the beginning of May onwards (Humphreys, 2007).

Due to interactions between different sources on-farm, reducing ammonia emissions requires a number of mitigation strategies working together including balancing N in the diet, incorporation of manures into arable lands where possible, the covering of manure storage facilities and by band spreading or injecting animal slurries (Sommer and Hutchings, 1995; Webb *et al*. 2005).When all these actions are taken then there is potential to reduce ammonia losses by up to 75% of the total N excreted (Kirchmann *et al*. 1998). In relation to the proportion of ammonia gas emitted through the use of mineral N fertilizers and in particular urea, a number of steps can be taken to minimise losses to the environment.

Appropriate rates of urea application need to be used in order to achieve the optimal protein content of grazing and conservation swards (Kirchmann *et al*. 1998) especially as volatilisation tends to increase with increasing rate of application. Ideally <40kg N/ha should be used on grazing swards which are less of a risk than those rates applied for silage conservation which can often be in excess of 80 kg N/ha, which in this case may necessitate the use of alternative fertilizer types. The timing of urea application in relation to weather can also be critical to reducing losses (Forrestal *et al*. 2016). Urea should typically be applied in damp rather than dry conditions and ideally applications should not be followed by sunny, windy conditions. Other recommendations include applying urea at least ten days prior to applying Lime and to wait at least three months to apply urea after the application of lime. The application of urea needs to avoid slurry application by at least ten days either side of the slurry spreading event. Applying urea into a crop canopy also provides protection from direct sunlight and lowers air flow over urea granules (Pain *et al*. 1999) which can also result in reducing losses and may tie in well with a blanket fertilizer application strategy as opposed to the more traditional strategy where fertilizer is applied a day or two after defoliation. Incorporating urea into the soil when reseeding will also reduce ammonia losses but care must be taken by avoiding placing urea with seed as urea hydrolysis causes the accumulation of NO_2^- which can damage seed, seedlings and young plants (Gioacchini *et al*. 2002).

The use of the urease inhibitor N-(N-butyl) thiophosphoric triamide (nBTPT) or (NBPT) to stabilise urea and retard the urea hydrolysis process has proven to be one of the most successful compounds at reducing ammonia emissions from surface applied urea and probably represent the most beneficial step that can be taken to reduce losses (Forrestal *et al*. 2015; Harty *et al*. 2016).

Forrestal *et al*. (2015) in a field experiment at two sites using wind tunnels evaluated ammonia loss from a number of fertilizer types applied at a rate of 200kg N/ha over five equal applications. Losses from CAN were approximately 4% whereas losses from unamended urea averaged 25.1% in one site and 30.6% in the other with losses ranging from 7.5 to 52.8% across sites and applications. When NBPT was added to urea ammonia losses were dramatically reduced by up to 78.5%. Watson *et al*. (1994) in a laboratory study also examined the effect of amending urea with different proportions of NBPT doing so on sixteen different grassland soil types. Applications using unamended urea resulted in ammonia losses ranging from 5.8 to 39%, of N applied. The effectiveness of NBPT varied on different soil types, however, the reduction potential by using inhibitors was significant on all soils; as it was shown that by adding NBPT at a concentration of 0.092% (w/w) it was able to reduce ammonia losses on any given soil by up to 90%. Gioacchini *et al*. (2002) also showed using a lysimeter study that the physio-chemical properties of soils affected the performance of NBPT on volatilisation levels. On clay loam soils losses of ammonia were reduced by 47% and on sandy loam soils volatilisation losses were reduced by up to 89%. All three experiments highlight the potential for inhibitors such as NBPT to greatly reduce N loss via volatilisation when incorporated into ammonium based fertilizers.

2.5.3 Denitrification of Nitrate

Denitrification represents a major pathway of loss of N deposited by grazing livestock in the form of dung and urine and is the most important of all three loss mechanisms in relation to fertilizer N used in grassland systems in Ireland and across the world (Jarvis *et al*. 1998; Steinfeld, 2006). Increased N losses via denitrification from agricultural soils is linked to a global increase in the use of fertilizer N in agriculture over a number of years (Harty *et al*. 2016). High N application rates, at any one time, can lead to reduced utilization efficiency of fertilizer N. This in turn further increases the likelihood of N fertilizers becoming a major source of loss of N through denitrification (Ryan *et al*. 1998; Ledgard *et al*. 1999, Roche *et al*. 2016).

The process of denitrification involves the reduction of nitrate, mainly by aerobic bacteria under soil conditions where there is a low oxygen (hypoxic) level or a complete absence of oxygen (anoxic or anaerobic) in the soil and results in the formation of Nitric oxide (NO), Nitrous oxide (N_2O) and Di-nitrogen (N_2) gases, which are then lost to the atmosphere (Jarvis and Hatch, 1994; Burchill, *et al*. 2014; Selbie *et al*. 2015). Nitric oxide and Nitrous oxide are important greenhouse gases and agriculture represents their largest emission source (Reay *et al*. 2012). Di-nitrogen unlike the other two reactive gases is an environmentally benign gas making up in excess of 79% of breathable air, however, similar to Nitric and Nitrous oxide, loss of applied N in the form of di-Nitrogen represents a decreased efficiency in fertilizer N use and an economic cost to the farmer (Selbie *et al*. 2015).

The rate of denitrification depends primarily on the organic carbon and nitrate content in soils, soil temperature, soil oxygen levels, soil pH and the presence of nitrifying bacteria. In general the higher the soil temperature (≥4°C), nitrate and carbon content and the lower the soil oxygen level then the higher the rate of denitrification (Jarvis *et al*. 1991, Ryan *et al*. 1998, Scholefield *et al*. 2000).

Denitrification predominantly occurs in the top 0-10 cm of the soil layer (Ryan *et al*. 1998) but can also occur in the subsoil at depths of over a meter deep (Weier *et al*. 1991) if adequate organic carbon remains available and in some instances up to six meters deep under long term grassland pastures with high N applications (Jarvis and Hatch, 1994). In terms of field measurements, accurate estimation of total denitrification is made difficult (Luo *et al*. 2000) because of spatial variation caused by the random distribution of denitrifying hot spots and uneven urine deposition and temporal variation caused in the main by rainfall and fertilizer N application events (Jarvis *et al*. 1991; Cantarel, *et al*. 2012).

Soil texture is one of the most critical factors affecting rates of denitrification as it influences soil drainage and soil water holding capacity which subsequently reduce the availability of free oxygen in the soil (De Klein and Van Logtestijn, 1996; Skiba *et al*. 1998). Coarse soil textures tend to have good soil pore space and allow for water to be more freely drained from these soils allowing the soil to remain aerated. In contrast finer soil textures tend to have smaller pore space and tend to become waterlogged more easily. As a consequence the percentage of water filled pore space (WFPS) tends to be higher with air between soil particles now being displaced by water which results in anaerobic conditions and as a result these soils display higher rates of denitrification.

Burchill *et al*. (2016) examined the N balance of a grass based dairy system in Ireland on a predominantly poorly drained gley soil (29% clay, 36% silt and 34% sand in 0-10cm) which is seasonally wet and waterlogged. The results indicated this soil was more prone to N losses via denitrification as opposed to losses through leaching. Loss of N via leaching amounted to 6.1 % (16.4 kg N/ha) of overall N losses, whereas losses via denitrification were far more substantial and amounted to 51.7% (139.1 kg N/ha), 8% as nitrous oxide and 43.7% as di-nitrogen gas, respectively. As well as being wet and lowering the amount of oxygen in the soil, the site also met many of the other factors which are conducive to potentially higher rates of denitrification such as an adequate supply of organic carbon, 512 g/kg, sufficient total N content, 54g/kg and a soil bulk density and soil pH of 0.87 g/cm3 and 6.2 respectively, in the top 10 cm of the soil layer. Other such studies (van der Salm *et al*. 2007) also estimated losses via denitrification and leaching from grass based dairy systems on heavy clay soils in the Netherlands with low permeability and a shallow water table and soil characteristics similar to those examined by Burchill *et al*. (2016).The results showed that 25% of the N applied in the form of fertilizer N and slurry were lost to the environment. These losses were in the form of N lost via leaching which were again low, 15 kg N/ha, representing 13% of overall N loss with the remaining 87% of loss being attributed to denitrification, which averaged 100 kg N/ha/yr over the duration of the trial, levels very similar to that estimated by Burchill *et al*. (2016).

In contrast coarse textured soils such as sandy loam soils which are relatively freer draining tend to have greater potential for N loss via leaching as opposed to loss via denitrification. Losses via denitrification on these soils under intensive stocking rates (3.3 LU/ha) and intensive fertilizer application rates (300 to 400 kg N/ha) typically only ranged from 3 to 34 Kg N/ha/yr, (Jordan, 1989; Ruz-Jerez *et al*. 1994; Ledgard *et al*. 1999).

In terms of fertilizer type nitrate based fertilizers (CAN/AN) tend to have greater potential for loss of N through denitrification compared with ammonium based fertilizers such as urea. Jordan (1989) found that rates of denitrification were three-fold for CAN versus urea and highest rates of denitrification (3.7 kg N/ha/day) occurred on the clay soil when near field capacity in days following the application of a high rate (94 kg N/ha) of CAN. This raises the potential for reducing N_2O emission by switching from CAN to urea based fertilizers.

Harty *et al*. (2016) conducted an experiment over two years at three locations (Johnstown Castle 52°18’27N, 6°30’14W, Moorepark 52°9’27N, 8°14’42W and Hillsborough 54°27’827N 6°04’578W) across Ireland evaluating N_2O emissions from the application of CAN, urea, urea + NBPT, urea + DCD and urea + NBPT + DCD to grassland plots at a rate of 200 kg N/ha. Results indicated that N2O emissions were significantly affected by soil type and climatic conditions and fertilizer formulation. The highest levels of emissions were associated with the most northerly site which had the lowest soil temperatures, the highest WFPS and the most poorly drained soils of all three sites. In general at all sites CAN was associated with the highest levels of N_2O emissions. The emission factor for CAN averaged 1.49% over all sites (range 0.58–3.81%) whereas for urea formulations the average was 0.25% (range 0.1–0.49%). Amending urea with NBPT resulted in an average emission factor of 0.40%. These results showed that replacing CAN with urea has the potential to reduce N_2O emissions and that even though there was an increase in ammonia emissions when urea was amended with NBPT, this formulation may still be an option in scenarios where there is a high risk of volatilisation from the use of urea.

The use of DCD also proved to be highly effective in reducing N_2O emissions but due to it being more expensive than NBPT, it has potential to negatively impact the effectiveness of NBPT (Forrestal *et al*. 2015) and fears over its potential to cross into the human food chain (Lucas, 2013), NBPT is the preferred choice of inhibitor.

High rates of fertilizer N exhibit higher rates of denitrification than unfertilised grass swards and that rates of denitrification can increase substantially and linearly with increasing fertilizer rates of between 100 to 500 kg N/ha (Jarvis *et al*. 1991; Watson *et al*. 1992b) with wetter soils having greater potential for loss via denitrification in comparison to freer draining soils (Harty *et al*. 2016). The spreading therefore of individually high applications of fertilizer and the application of N to soil at times when it is wet and is likely to remain wet for an extended period should be avoided in order to reduce the denitrification of applied fertilizer N (Humphreys *et al*. 2002b).

2.5.4 Leaching of Nitrate

Nitrate leaching from agricultural production systems is blamed for rising nitrate concentrations in ground and surface water worldwide (Di and Cameron, 2002). Leaching of nitrate occurs when the downward gravitational pull on soil water is greater than that of the upward pull of soil water by evapotranspiration by plant roots causing nitrate to be washed out of the root zone (Humphreys *et al*. 2002b). Nitrate may then move down through the soil profile and eventually reach groundwater supplies, potentially causing eutrophication of water bodies (Bhatnagar and Sillanpää, 2011) and elevated levels of nitrate in water used for human consumption, which may be responsible for the causation of specific cancers and may have a link, albeit dubious, to the incidence of methemoglobinemia (blue baby syndrome) in infants (Van Grinsven *et al*. 2006).

As a result of these perceived risks to the environment and human health a maximum admissible concentration (MAC) of 11.3 mg/l nitrate-N for drainage water from agriculture was defined in an EC Directive (EC 1980). A decade later the Nitrates directive (1991) was formulated and forms an integral part of the Water Framework directive (2000) and has the two main aims of preventing nitrates from agricultural sources polluting ground and surface waters and encouraging good farming practices within the agricultural community. The legislation allowed for the identification of lands where drainage water could lead to elevated nitrate concentrations (≥50mg nitrate/l or ≥11.3 mg/l nitrate-N) in surrounding water and designated them as nitrate vulnerable zones (NVZ's) with restrictions therein being placed on the quantities, spreading periods and conditions (steep slopes, frozen ground, proximity to water courses) for applying mineral N fertilizers. In Ireland the Nitrates Directive was not implemented on a regional basis with designated NVZ'S as in other countries but rather implemented uniformly across the country (Buckley, 2012).

The majority of leaching occurs when rainfall amounts exceed evapotranspiration levels (Jarvis and Aarts, 2000) and therefore most commonly occurs in late autumn, winter and early spring (Kolenbrander, 1981; Scholefield *et al*. 1993; Watson, 2001), but can occur at any time when N input exceeds a crops capacity to utilise available N (Jalali, 2005). N leached from the root zone is mainly in the form of nitrate as opposed to ammonium as nitrate is more easily moved because its ions are negatively charged and are repelled by clay and organic particles which are also negatively charged whereas ammonium ions are positively charged and held more tightly by the soil structure (Watson, 2001).

Leaching is influenced by many factors, some of which include soil type, temperature, water regime, grazing, fertilizer application rate and fertilizer type with the amount of leaching being controlled mainly by the level of excess precipitation and the quantity of nitrate in the soil available for leaching at the beginning of the period of water movement (Kolenbrander, 1981; Whitehead, 1995; Addiscott, 1996; Di and Cameron, 2002).

Nitrate leaching typically occurs under soil conditions which are opposite to those where denitrification is likely to occur. Nitrate in solution can be carried through the soil via either by micropore or macropore flow (Sugita and Nakane, 2007), the latter being the much faster method of flow. Finer textured clay soils tend to exhibit micropore flow as they have smaller pore space in comparison to coarse sandy soils which exhibit macropore flow as they have larger particle sizes and therefore larger pore space and thus can be described as "free draining soils" (Humphreys *et al*. 2002b). As a consequence nitrate in water in the more mobile macropore phase is far more susceptible to loss via leaching than that in the more immobile micropore phase (Addiscott, 1996; Scholefield *et al*. 1996; Gärdenäs *et al*. 2005). However, clay soils tend to expand when wet and contract when dry, this shrinking can lead to the development of cracks or fissures in the soil profile which can lead to preferential pathways of flow increasing the risk of leaching from clay soils (Addiscott, 1996).

In clay soils the amount of water draining through the soil that is needed to remove all the nitrate will be far greater than the amount needed in a sandy soil as more of the nitrate is held in the more immobile micropore phase (Addiscott, 1996) resulting in denitrification as opposed to leaching of N. The greater the degree of macroporosity as in sandy soils, the greater the preferential flow, allowing leaching to commence before the soil has reached field capacity (Whitehead, 1995; Wang *et al*. 2012) resulting in the greatest risk of nutrient loss occurring during an intense period of rainfall or artificial irrigation (Williams *et al*. 2003; Jalali, 2005). Increased volumes of water will have a dilution effect and will result in the concentration of nitrate in drainage water to appear lower masking the fact that there is an overall increase in the amount of nitrate leached. As rainfall events cannot be controlled the best approach to therefore reduce loss is to minimise the quantity of nitrate available for loss by matching the total supply of N over the growing season with the requirements of the grass sward (Whitehead, 1995).

An accurate estimate of nitrate being leached is critical to environmental impact studies (Basso and Ritchie, 2005). Urine deposition is the most important source of leached nitrate in a grazing system (Di and Cameron, 2007), however, the focus here will be on the contribution of fertilizer N to leaching losses by examining a number of studies that have been performed, especially on free draining soils which are deemed more vulnerable to nitrate leaching (Addiscott, 1996; Ryan *et al*. 2006) and which used a variety of sampling methods including drainage lysimeters, porous ceramic suction cups, deep well bore holes and v-notch drainage ditches. The results then used to help quantify leaching losses and develop models such as NCYCLE IRL (Prado *et al*. 2006) that integrate all data collected on N cycling in grassland and therefore allows for the identification of mitigation strategies to help reduce the amount of N available for potential loss via leaching.

In the UK (Dowdell and Webster, 1980) applied 15 labelled N in the form of calcium nitrate at a rate of 400 kg N/ha to monolith lysimeters containing free draining sandy loam soil (10% clay, 8% silt, 80% sand) growing perennial ryegrass swards. The lysimeters were broken into three subsets with fertilisation of the first subset beginning in year 1 (series A), year 2 for the second subset (series B) and year 3 for the final subset (series C). All treatments received 6 dressings of 15labelled N fertilizer in only one calendar year and were monitored for several years to observe residual effects of N application. Fertilizer N accounted for 60-70% of the total N lost in the first winter but losses via leaching only accounted for 2-5% of fertilizer N applied. Averaged over the first three winters after application fertilizer accounted for 45-60% of N loss and the residual effects of N application were determined to be evident for a period of between six and nine years post application. Losses via leaching in the winters following the first winter were insignificant never exceeding 0.1% of N applied. Of greater interest was the observed large variation between individual lysimeters (50-105%) highlighting differences in crop uptake and variation in the physiology of individual lysimeter soil monoliths. Also of note were that greatest losses followed periods of adverse growing conditions such as low rainfall leading to the large losses (29.7 mg/l nitrate-N) following the dry winter and dry summer in the third year of the experiment.

(Watson *et al*. 2000) also conducted a long term nitrate leaching experiment over nine years on free draining soils in Northern Ireland, growing perennial ryegrass, fertilizer N was applied each year in the form of CAN at five different rates ranging from 100 to 500 kg N/ha. Plots were 0.2 ha in area and were hydrologically isolated and artificially drained to v-notch weirs with flow-proportional monitoring of drainage water. Losses from application rates above 300 kg N/ha resulted in mean annual concentrations of nitrate in drainage water exceeding the MAC. Losses on grazing plots that received 300 kg N/ha had a nitrate concentration in drainage water of 8.5 mg/l nitrate-N. The relationship between rate of N application and nitrate leached was linear with approximately 13% of the N applied being lost to drainage water. There was a large range in losses of 5 to 23% between individual years, mainly due to the variations in climatic conditions such as temperature and rainfall amount with, for example, highest losses being observed in the winter of the fifth year of the experiment following the previous dry summer.

Ryan *et al*. (2006) examined nitrate leaching on a free draining sandy loam soil in the south of Ireland on an intensively managed (2.38 LU/ha and fertilizer N input of 319 kg N/ha using urea and CAN) dairy farm using porous ceramic suction cups at 1 metre depth over a four year period. Ground water monitoring (Bartley and Johnston, 2005) using deep well boreholes was also conducted in conjunction with the shallow depth field experiment on the site over the same period. Nitrate leaching at 1 metre depth over the experimental period averaged 8.2 mg/l nitrate-N which equates to a loss of 10% of total N input and is very similar to losses reported at comparable fertilizer N inputs by (Watson *et al*. 2000) and strengthens the determination that annual fertilizer N inputs below 300 kg N/ha lead to nitrate concentrations that do not exceed the MAC (Kolenbrander, 1981; Ledgard *et al*. 1997; Watson *et al*. 2000). Groundwater measurements averaged 11.7 mg/l nitrate-N over a three year period. As the ground water levels exceeded the MAC continuous monitoring of groundwater was implemented in the years following the experiment with the farm implementing a much more efficient nutrient management plan (Huebsch *et al*. 2013).

On the same site in 2011, a 3-year experiment began using porous ceramic cups to a depth of one metre on again an intensively managed grazing system (2.51 – 3.28 LU/ha and fertilizer N input of 209 kg N/ha using urea and CAN) (McCarthy *et al*. 2015). Average nitrate concentrations were approximately 26.0 mg/l nitrate-N which are well in excess of the MAC and indicate large losses which are reflected in a mean NUE of 46% with fertilizer being the main source (89%) of imported N. However Huebsch *et al*. (2013) had monitored ground water nitrate concentrations between the experiment conducted by Ryan *et al*. (2006) and up to and including the most recent ceramic cup measurement period and found nitrate concentrations in groundwater to be only 7.0 mg/l nitrate-N. The disparity between shallow and deep water nitrate concentrations highlight the fact that N concentrations at one metre deep may not always reflect those in surface or ground waters (Ryan *et al*. 2006) due the complex nature of N transformations in soil and movement of N from surface to groundwater. The low ground water levels recorded by (Huebsch *et al*. 2013) also showed that changes in farm practices that reduce agronomic loadings have a rapid and lasting effect on groundwater hydrochemistry (Bartley and Johnston, 2005).

On a comparative note (Humphreys *et al*. 2008) measured nitrate concentrations beneath grazing swards and found concentrations of only 0.9 mg/l nitrate-N in systems where there was stocking rate of 2.5 LU/ha and a fertilizer N input of 350 kg N/ha. However this system was based on a clay loam soil with impeded drainage as opposed to free draining soils. The results are indicative of more finely textured soils where denitrification is the predominant form of loss (Addiscott, 1996; Watson, 2001; Ryan *et al*. 2006) and where losses due to leaching only exceed 2.5 mg/l nitrate-N when fertilizer N input reaches 400 kg N/ha.

2.6 Measurement Techniques

2.6.1 Field plot experiments

Determining the response of grassland to applied fertilizer N in terms of grass DM yield, N concentration, N uptake in grass and the apparent recovery of fertilizer N (ARFN) invariably requires the use of field plot experiments. These experiments are usually comprised of a series of grass sward plots which are predominantly made up of perennial ryegrass (*Lolium perenne L*. cv. Magella) cultivars and are arranged in a randomised design in order to ensure unbiased treatment means and experimental error (Bailey, 2008). The methodology as described by Corrall and Fenlon (1978) is then often widely used to carry out on a weekly basis the mechanical harvesting of plots to which treatments have already been imposed.

The use of different types, rates and timing of fertilizer N application allow for a series of responses to be developed for each application strategy. These responses can be then used as a basis for determining the agronomically optimum fertilizer N strategy.

2.6.2 Apparent Recovery of Fertilizer Nitrogen (ARFN)

Estimating fertilizer N recovery fractions in grass involves the use of either the isotopic-dilution technique or the non-isotopic difference technique (Harmsen, 2003).

In the isotopic-dilution technique the amount of applied N that is recovered by the growing crop is estimated from the total N uptake and N isotope ratio analysis of herbage material from treated plots (Hauck and Bremner, 1976). The non-isotopic difference technique involves using plots in the experimental design which remain unfertilized and so consequently act as control plots (Broadbent, 1981). The N uptake value in the unfertilised control plots is then subtracted from N uptake values in fertilized plots (Harmsen, 2003) with the difference between them being attributed to the impact of fertilizer N input. As such the ARFN can then be expressed as a percentage of the fertilised N applied (Murphy *et al*. 2013).

In the absence of fertilizer N grass predominantly receives its N supply from either the atmospheric deposition of N, biological N-fixation or by mineralisation of SOM. The assumption is that there is no alteration in the amount of N being taken up by the crop as a result of applying fertilizer N. However, some workers do contend that the addition of fertilizer to swards does indeed cause an effect on mineralisation/immobilisation processes (Hart *et al*. 1986, Schnier, 1994; Lovell and Hatch, 1997; Hatch *et al*. 2002) and that an added nitrogen interaction (ANI) may occur.

The effect can be either positive or negative and can be described as “real” as in the case where the addition of extra N results in a priming phenomenon (Jenkinson *et al*. 1985) whereby SOM turnover is accelerated/retarded by increased soil microbial biomass or microbial activity, increased rooting depth is promoted and elements other than N which may be deficient in the background are supplied. Real ANI’s generally tend to result in an overestimation of N recovery (Rao *et al*. 1991). In isotopic dilution’s “apparent” ANI’s refer to pool substitution where labelled N is exchanged with native soil N (Kuzyakov *et al*. 2000) often resulting in the underestimation of N recovery.

In a scenario where the rate of fertilizer being applied is low relative to the amount of soil N involved in mineralisation/immobilisation processes, N recoveries tend to be 10% lower in dilution versus difference techniques (Hoekstra *et al*. 2010). When N fertilizer application rates are high compared with crop needs, recovery estimations tend to be 10% higher in isotopic dilution versus agronomic methods (Schröder, 2005). As can be seen both methods have their drawbacks and can be looked upon with equal suspicion (Rao *et al*. 1991). However, in a comparison of both methods (Harmsen, 2003) determined that from an agronomic point of view the difference technique is the preferred option as it is a measure of the overall effect of fertilizer N application on DM yield and N uptake. This fact has allowed for recent work to also use agronomic techniques as a means of determining N recovery.

For example, Lalor *et al*. (2011) used a field plot experiment to examine the effect of method and timing of application on the nitrogen fertilizer replacement (NFRV) value of cattle slurry. The experimental design included plots that received slurry application by various methods and also control plots where there was no application of slurry throughout the measurement period. These control plots were instead divided into six equal area sections with each section receiving either 0, 30, 60, 90, 120 or 150 kg N/ha in the form of mineral N fertilizer. Herbage was harvested mechanically from plots and DM yield and N concentration figures were determined and used to calculate apparent N recovery. This method allowed the NFRV of the slurry to be calculated based on the apparent N recovery of slurry N relative to mineral N fertilizer.

Minogue *et al*. (2010) assessed the fertilizer potential of soiled water (SW) as a replacement for mineral fertilizer N in an experimental field plot study. Treatments consisted of nine separate application times at four rates of 0, 15, 22 and 30 kg N/ha and were applied in the form of either a SW application or mineral fertilizer N in the form of CAN. Again using this method enabled comparisons to be made in terms of DM yield between each individual timing, method and rate of application of SW relative to mineral N fertilizer applications and response curves accordingly determined. Mean NFRV's for each of the SW treatments were also calculated as the SW DM yield response divided by the mineral fertilizer N DM yield response, expressed as a percentage.

2.7 Overview

The input of mineral N fertilizers is an integral part of grassland based systems of production in Ireland. A planned approach to the application of such an input within the allowed annual timeframe under Irish regulations, is essential to obtain the greatest benefit in terms of cost effective grass DM production. At the same time, any approach must be mindful of potential inefficiencies in its use as they may lead to both economic losses for the farmer and potential loss of applied N to ground and surface waters and to the atmosphere.

This thesis carried out two experiments, between 2004 and 2006, recording the effect that the application of fertilizer N had on perennial ryegrass swards. The measurements taken related to DM production, N uptake and N recovery in grass. With the results, this thesis aimed to identify a structured application strategy from the first fertilizer N application in spring to the last N application in autumn.

Chapter 3 Effects of Early Spring N-fertilization Strategies on Grass Production and Nitrogen Recovery

3.1 Abstract

Application rate and application date of fertilizer nitrogen (N) are important factors determining grass production response and N recovery by grassland in spring. This study was conducted at two sites with different soil types (sandy loam and clay loam) in Ireland in spring 2005 and 2006. In comparison with a non-fertilized (zero–N) control, urea N was applied at rates of 60 and 90 kg N/ha either as single or split applications on eight dates ranging between 11 January and 14 March. Grass was harvested on four occasions between 21 February and 25 April. Split fertilizer N applications provided the best outcome in terms of grass DM production, apparent recovery of fertilizer N (ARFN) and cost of additional grass produced compared with single applications. Likewise, in this study the optimum date to commence fertilizer N application was 21 January combined with a second application on 26 February in terms of the cost effectiveness of the fertilizer N input to increase grass DM production.

Keywords: apparent recovery of fertilizer nitrogen, application date, application rate, grass production, nitrogen uptake

3.2 Introduction

Grazed grass constitutes 60 to 75% of the diet of dairy cows in Ireland and is widely recognized as the cheapest form of feed for milk production. Accumulated evidence has shown that in a typical Irish system of dairy production, a compact calving pattern in springtime in conjunction with an early turnout date to pasture has clear economic advantages (Dillon and Crosse, 1994; Sayers and Mayne, 2001; Dillon *et al*. 2002; Kennedy *et al.* 2005; Kennedy *et al.* 2007; McEvoy *et al*. 2010). However, in Ireland there is little net growth of grass during the winter period due to low temperatures and low incidental solar radiation (Hennessy *et al.* 2008). As a result management strategies are necessary to increase grass availability in the late winter and early spring. The application of fertilizer N in spring has an important role in achieving this objective (Laidlaw *et al.* 2000; O'Donovan *et al*. 2004).

During recent decades there have been a number of studies examining the impacts of application date and application rate of fertilizer N on grass production for grazing in early spring (Murphy, 1977; Stevens *et al.* 1989; Long *et al.* 1991; Laidlaw *et al.* 2000; O'Donovan *et al.* 2004; Murphy *et al.* 2013). However, these experiments usually only entailed comparing single applications of fertilizer N applied at a range of application rates and on a range of application dates, which were typically between early January and mid-March. Grass production response was quantified in terms of grass harvested on one or two dates, typically in mid-March and/or mid-April. Results suggest that single large applications gave the highest grass production response; whereas the optimum date for application of fertilizer N was less clearly identifiable. On Irish dairy farms fertilizer N is typically applied to grassland using a number of applications throughout the growing season with the purpose of increasing grass availability for grazing livestock (Humphreys *et al*. 2003b; Dillon *et al*. 2009). In certain instances this can be on up to ten occasions per year (Treacy, 2008). However, fertilizer N has become much more expensive relative to farm gate product prices in recent years (Humphreys *et al*. 2012) and there is increasing pressure in many western European countries to improve ARFN in order to lower any potential negative impact on the environment (Van Grinsven *et al.* 2013).

While single large applications in spring have been shown to give the best grass production responses they are also associated with lower ARFN and in most instances the residual impact on subsequent grass production later in the spring was not taken into account. Therefore, the objective of this study was to investigate whether combinations of two (split) applications of fertilizer N would result in higher grass production and ARFN in comparison with single applications of fertilizer N in spring. Specific objectives were to (a) determine the effect of single or split N application on grass production and ARFN, and (b) identify the most appropriate dates for fertilizer N application during springtime.

3.3 Materials and Methods

3.3.1 Experimental site characteristics

The experiment was conducted at the Teagasc Animal and Grassland Research and Innovation Centre at Moorepark (52° 09' N, 08° 15' W; altitude 50 m ASL) and at the Teagasc Solohead Research Farm (52° 51' N; 08° 21' W; altitude 150 m ASL).

The topography of the Moorepark site is gently rolling. The soil is classified as a free-draining acid brown earth (Cambisol) of sandy loam to loam texture. Soil pH, total N and total C content in the surface 10 cm of soil were 6.5, 0.48% and 4.48%, respectively. The site drains quickly following periods of high rainfall. Total annual rainfall amounts to approximately 1000mm with soil temperature at 10cm typically averaging 11°C across the year.

The topography of the Solohead site is relatively flat. The soil is classified as a poorly drained gley (Gleysol; 90%) and a grey-brown podzolic (10%) with a clay loam texture. Soil pH, total N and total C content in the surface 10 cm of soil were 6.5, 0.54% and 5.35%, respectively. The site tends to remain water logged after periods of high rainfall. Total annual rainfall can amount to 1050mm with mean soil temperature at 10cm typically around 10°C over the year.

The local climate at both sites is maritime in nature and there is a long potential growing season of between 270 and 300 days (Brereton, 1995).

3.3.2 Experimental layout and design

This study was conducted at both sites in 2005 and 2006. Prior to this study, the grassland had been renovated at both sites in 1999 and sown with perennial ryegrass (*Lolium perenne L.* cv. Magella). Both sites were used for pasture based dairy production following renovation until prior to the commencement of the study in 2005. A soil test before the beginning of the study indicated no requirement for the application of lime and phosphorous (P) and potassium (K) levels were also sufficient to meet the grass growth requirements over the experimental period (soil P index 4: 18.9 and 35.6 mg/l Morgans P at Moorepark and Solohead respectively and soil K index 4: >150 mg/l at both sites).

Grassland plots (3m x 5 m) were laid out in a randomized complete block design. Three blocks were laid down at each site in 2005 and the number of blocks was increased to four at each site in 2006. Within each block, there were 32 main plots. There were eight application rates of fertilizer N including non-fertilized control (0+0; Table 3.1). The eight application rates were applied as a single or as a combination of two (split) applications of a total of 60 kg/ha or 90 kg/ha of fertilizer N (Table 3.1).

Each of these eight fertilizer N application treatments were applied on eight dates during the spring. Where applications were split, there was approximately five weeks between the first and second application (Table 3.1). Fertilizer N was applied by hand in the form of fine crystalline solid of urea (46% N).

Each of the thirty-two main plots were divided into four sub-plots measuring 0.75 m × 5 m each. Each sub-plot was randomly assigned to each of four harvest dates: 21 February

(H1), 14 March (H2), 4 April (H3) and 25 April (H4). Therefore, grass was harvested from one sub-plot on each harvest date, and the same area of each sub-plot was only harvested once during the experimental period in each year; thus there was no harvesting of any subsequent regrowth. Grass harvesting was performed using a Honda rotary blade lawnmower (HRH 535; Honda, Swepsonville, NC, USA) with a cutting blade width of 0.55 m and cutting height of 4 cm. A strip 0.55 m wide and 5 m long was harvested along the centre of each sub-plot. This allowed a border of approximately 0.20 m between each sub-plot.

Table 3.1 Application rates and dates (D) of fertilizer N and harvest dates (H) of grass in this study

Application rate (kg/ha of fertilizer N)		
	Rate on first application date	Rate on second application date
0+0	0	0
0+60	0	60
0+90	0	90
30+30	30	30
30+60	30	60
60+0	60	0
60+30	60	30
90+0	90	0
Application date of fertilizer N		
	First date	Second date
D1	11-Jan	21-Feb
D2	21-Jan	26-Feb
D3	01-Feb	07-Mar
D4	11-Feb	14-Mar
Grass harvest dates		
H1	21-Feb	
H2	14-Mar	
H3	4-Apr	
H4	25-Apr	

3.3.3 Grass sampling and analysis

Harvested grass from each sub-plot was collected and weighed. A sub-sample of 100 g was dried for 16 h at 98°C in a forced air oven to a constant weight to determine dry matter (DM) content. A second 100 g sub-sample was dried at 40°C in forced draught oven for 48 h, milled to pass a 2 mm screen. The concentration of N in the grass was determined by a LECO 528 auto analyser (LECO Corporation, St. Joseph, MI, USA).

3.3.4 Uptake of N in grass and ARFN

Uptake of N in grass was calculated by multiplying grass DM yield by the N concentration in harvested grass. It was assumed that biological N fixation was negligible because there was no clover in the swards and N deposition in the region is low at approximately 6 kg/ha per year (Jordan *et al.* 1997; Necpálová *et al*. 2013). Apparent recovery of fertilizer N (nitrogen recovery efficiency) was calculated as the difference in N uptake between fertilized and unfertilized (zero-N) plots in each replicated block between application of fertilizer N and harvest of the grass and expressing this as a proportion of the total fertilizer N applied.

$$\text{ARFN (\%)} = (N_U - N_0)/N_F$$

N_U = N uptake in fertilized plots

N_0 = N uptake in zero-N plots

N_F = Applied fertilizer N

The ARFN was determined for H1, H3 and H4 for both years. The ARFN was not determined for later single applications at H1 as the fertilizer N for those combinations had not been applied at that stage. Also as only some and not all of the later single and split applications had received their full rate of fertilizer N applied by the time of H2, ARFN was not determined for any of the application rate or date combinations at H2.

3.3.5 Calculating the cost of additional grass DM

The cost of fertilizer N in the form of urea (46% N and €0.85/kg of N) was based on the average cost between 2008 and 2017 according to the central statistics office (CSO, 2018). Thus the cost of N applied at 60kg and 90kg was €51 and €77, respectively. Each additional kg of grass grown was estimated to contain 3 g/kg DM of P and 25 g/kg DM of K. The cost of fertilizer P was €2.55/kg and of fertilizer K was €0.78/kg based on the average cost of each between 2008 and 2017 (CSO, 2018). On this basis, the cost of fertilizer N applied and the imputed costs of P and K in the additional grass grown (as a consequence of the application of fertilizer N) were summed for the final harvest (25 April) for each plot in each year. A standard cost of €60/t of grass DM was included to account for ancillary costs. These were the opportunity cost of land at €50/t of grass DM, grassland renovation (every 20 years) at €7.50/t of grass DM and the application of lime (every five years) at €2.50/t of grass DM (Finneran *et al*. 2011; O'Donovan *et al*. 2011).

3.3.6 Statistical Analysis

The experiment was a randomized complete block combined over two locations with three replications in 2005 and four replications in 2006. Grass DM production and N uptake in grass DM for each harvest date in each year were subjected to ANOVA using MSTAT (Freed *et al*. 1989) and analyzed as a two factor (application date x application rate) examining the main effects of each factor and interactions between factors. For H1 and H2 grass DM production and N uptake in grass DM for six treatments were included in the ANOVA; the 0+60 and 0+90 treatments were not included because they had not received an application of fertilizer N at that stage of the study in either year. Likewise ARFN for H1, H3 and H4 in each year were subjected to ANOVA examining the main effects of each factor and interactions between factors. The cost of additional grass for H4 in each year was subjected to ANOVA examining the main effects of each factor and interactions between factors.

Single applications of fertilizer N at rates of 60 kg/ha and 90 kg/ha were applied on eight dates between 11 January and 14 March in both years at both sites during this study. The effect of application date of single applications of fertilizer N at rates of 60 kg/ha and 90 kg/ha on grass production response at each harvest date at each site was examined using linear or polynomial regression.

3.4 Results

3.4.1 Meteorological Data

Monthly rainfall and daily soil temperature at 10 cm depth during the experimental period and the 20-year average for both are presented in Figure 3.1. With the exception of March, monthly rainfall in 2005 was higher than in 2006 at both sites. Total rainfall during the period encompassing 1 Jan to 30 April was substantially higher in 2005 (316 mm for Moorepark and 318 mm for Solohead) than in 2006 (247 mm for Moorepark and 225 mm for Solohead). In both years daily soil temperature was lowest in February and highest in April. Average soil temperature was higher in 2005 (7.0°C) than in 2006 (6.3°C) at both sites and higher at Moorepark (7.1°C) than at Solohead (6.1°C).

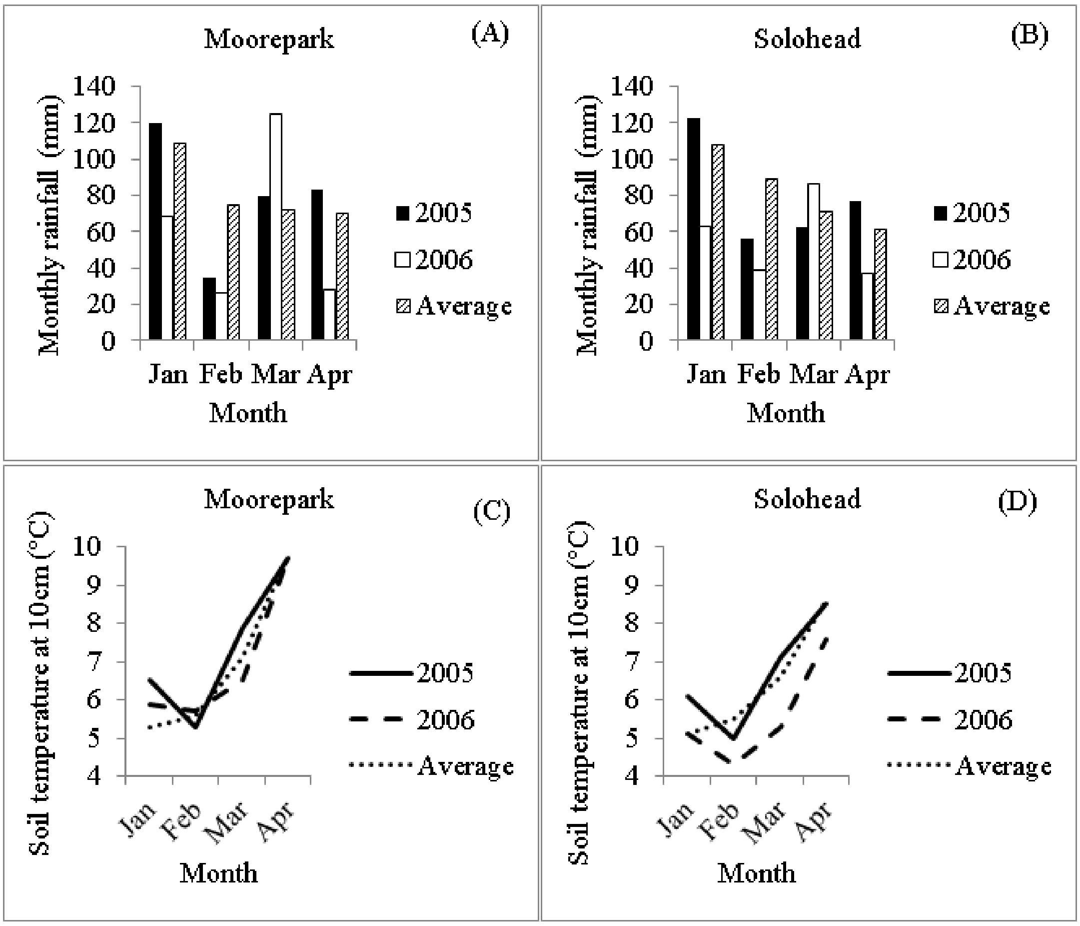


Figure 3.1 Monthly rainfall at (A) Moorepark and (B) Solohead and average monthly soil temperatures at 10 cm depth at (C) Moorepark and (D) Solohead in 2005, 2006 and 20-year average

3.4.2 Grass production

Grass DM yields increased with later harvest dates in both years (Table 3.2). There was no interaction between application date and application rate on any of the harvest dates in either year. In 2005 grass DM production declined with later fertilizer N application dates for H1 ($P<0.05$), H2 ($P<0.01$) and H3 ($P<0.01$) but not for H4 ($P>0.05$). In direct contrast to this in 2006 application date had no (P>0.05) effect on grass DM yields for H1, H2 and H3, but had a significant (P<0.01) effect on grass yields at H4, with a trend for the earlier application date (D1) to have higher grass yields than the later application dates (D3 and D4).

Application rate had a significant (P<0.01) effect on grass DM yield at every harvest in each year except H1 in 2006 (Table 3.2). In general at H1 in 2005 grass yield on the zero-N treatment (0+0) was significantly lower than those that were fertilized (30+30, 30+60, 60+0, 60+30, and 90+0). There was no difference (P>0.05) in grass yields between these latter fertilizer N application treatments. At H1 in 2006 fertilizer N application had no significant effect on grass DM yields.

At H2 in 2005 there was a clear trend for grass yields to increase with fertilizer N input in the earlier of the combined applications, with treatments that received 60 and 90 kg/ha of fertilizer N (60+0, 60+30, and 90+0) had higher (P<0.001) grass yields than treatments receiving 30 kg/ha (30+30, 30+60), which in turn were higher than the zero-N treatment. A similar but less pronounced trend was recorded at H2 in 2006 with the zero-N treatment producing significantly lower yield than those that were fertilized (30+30, 30+60, 60+0, 60+30, and 90+0) and there was no difference in grass yields between the latter treatments.

Table 3.2 The effects of fertilizer application rate, fertilizer N application date and harvest date (see Table 3.1) on grass dry matter (DM; kg/ha) production during the spring in 2005 and 2006 (data from both sites averaged in each year)

Year:	2005				2006			
Harvest date:	H1	H2	H3	H4	H1	H2	H3	H4
Application rate (R)								
0+0	517	734	1212	2162	334	344	688	1500
0+60			1727	3112			924	2263
0+90			1881	3224			1041	2532
30+30	669	899	1935	3106	373	410	1129	2402
30+60	597	939	1964	3361	364	411	1206	2551
60+0	681	991	1785	2956	365	457	1138	2384
60+30	626	944	1931	3198	372	452	1285	2686
90+0	688	1021	2038	3183	369	431	1205	2512
SEM	25.3	42.8	47.1	73.1	18.8	18.0	40.5	66.5
Application date (D)								
D1	668	988	1880	3091	362	428	1112	2484
D2	630	944	1822	2963	381	430	1121	2396
D3	624	905	1818	3063	370	400	1045	2237
D4	598	848	1717	3034	338	412	1030	2298
SEM	18.1	27.3	33.3	51.7	13.4	15.4	28.7	47.0
Level of significance								
Rate	***	**	***	***	NS	**	***	***
Date	*	**	**	NS	NS	NS	NS	**
R x D	NS	NS	NS	NS	NS	NS	NS	NS

*, P<0.05; **, P<0.01; ***, P<0.001, NS, Non-Significant.

In H3 in 2005 and 2006 there was a similar trend in grass yields to H2 with higher grass yields with increasing rates of fertilizer N in the earlier of the combined applications but much less clear cut in 2006 than 2005. In H4 in both years there was little difference in grass yields between treatments that received fertilizer N. At H4 averaged over all treatments there was an additional grass DM production response of 1000 kg/ha in 2005 and 975 kg/ha in 2006 compared with the treatment that received no fertilizer N input (0+0).

In general in 2005 and 2006, the split application of 60 kg/ha (30+30) resulted in higher grass DM production than, or was not different from, single applications of 60 kg/ha (0+60 and 60+0). The exceptions were H2 in both years when 60+0 > 30+30.
There were no detectable differences in grass DM production between 60+30 and 30+60 at each of the harvest dates in both years except for H4 in 2005, when (30+60) > (60+30). The 30+60 treatment had higher grass DM production than 0+90 at H2 in 2005 and H3 in 2006 and otherwise there were no differences between these two treatments. The 30+60 treatment had lower grass DM production than 90+0 at H1 and H2 in 2005 and, in contrast to this, 30+60 had higher grass DM production than 90+0 at H4 in 2005. There was no difference between these treatments at H3 in 2005 or for any of the other harvest dates in 2006.

3.4.3 Nitrogen uptake in grass

Similar to grass yields, N uptake in grass increased with later harvest date in both years. There was no interaction between application date and application rate for any of the harvest dates in either year (Table 3.3).

There was a trend for N uptake to decline with later application date at H1 in 2005 ($P<0.05$), H2 in 2005 ($P<0.001$). For these two harvests, application dates D1 and D2 had highest N uptake with N uptake decreasing with later application date; D4. There was no difference in N uptake between the application dates at H3 and H4 in 2005 and for all harvests in 2006.

Application rate had a significant ($P<0.05$) effect on N uptake at every harvest date in 2005 and 2006. At each of the harvests, plots that received fertilizer N had significantly greater uptake of N than the zero-N plots. Similar to grass yields differences between application rate treatments were more pronounced in 2005 than 2006. At the earlier harvest dates (H1 and H2) in both years there was a clear trend for N uptake in grass DM to be higher with increasing fertilizer N input in the earlier split of the combined application. This trend was somewhat diminished at H3 in both years and by H4 in both years the highest rates of N uptake were associated with treatments that combined inputs of fertilizer N in both the earlier and later splits (30+60 and 60+30) or where a greater proportion of N was in the later split (0+90).

Uptake of N was higher for 30+30 than 0+60 at H3 in both years, with no difference between these treatments at H4 in both years. In 2005 30+30 had higher N uptake than 60+0 at H3 and H4, whereas 60+0 had higher uptake at H2 in 2006. Otherwise there were no differences between the latter treatments.

At H1 in 2005 and H2 in 2006 60+30 had higher N uptake in grass DM than 30+60, while 30+60 had higher N uptake at H3 and H4 in 2005; otherwise there were no differences between these treatments at the other harvest dates in each year. The 30+60 treatment had higher N uptake than 0+90 at H3 in 2006, with no difference between these treatments at the other harvest dates in each year. At H1 in 2005 90+0 had higher uptake than 30+60 and 30+60 had higher uptake than 90+0 at H4 in 2005 and otherwise there were no differences in N uptake between these treatments at any of the other harvest dates in either year.

Table 3.3 The effects of fertilizer application rate, fertilizer N application date and harvest date (see Table 3.1) on N uptake in grass dry matter (kg/ha) during the spring in 2005 and 2006 (data from both sites averaged in each year)

Year:	2005				2006			
Harvest date:	H1	H2	H3	H4	H1	H2	H3	H4
Application rate (R)								
0+0	23.7	26.7	42.0	58.2	13.6	14.8	23.3	44.2
0+60			75.5	98.5			36.9	78.0
0+90			88.8	109.0			44.5	92.9
30+30	32.5	40.1	80.7	94.5	16.4	20.2	43.8	80.7
30+60	29.3	44.0	88.4	111.2	16.0	20.7	49.8	90.6
60+0	34.8	43.4	70.6	84.8	16.7	22.6	43.3	78.5
60+30	32.3	44.3	83.6	100.7	17.0	23.2	52.0	92.6
90+0	36.2	47.2	84.7	97.9	17.0	22.1	48.0	85.6
SEM	1.27	1.77	1.76	2.33	0.84	0.86	1.70	3.00
Application date (D)								
D1	33.2	43.9	78.2	94.3	16.0	21.2	43.4	84.2
D2	31.5	42.3	76.0	92.8	17.0	21.5	44.5	81.1
D3	31.5	41.2	78.1	94.8	16.5	19.9	41.7	76.8
D4	29.3	36.4	74.8	95.6	15.0	19.7	41.3	79.5
SEM	0.88	1.21	1.56	1.82	0.61	0.79	1.24	1.95
Level of significance								
Rate	***	***	***	***	*	***	***	***
Date	*	***	NS	NS	NS	NS	NS	NS
R x D	NS	NS	NS	NS	NS	NS	NS	NS

*, P<0.05; **, P<0.01; ***, P<0.001, NS, Non-Significant.

3.4.4 Apparent Recovery of Fertilizer Nitrogen (ARFN)

Averaged over both years ARFN increased from 0.13 at H1 to 0.41 at H3 and 0.54 at H4. However the rates of increase with later harvest dates differed between years; AFRN was 0.20, 0.52 and 0.54 in 2005 and 0.07, 0.29 and 0.54 in 2006 for H1, H3 and H4, respectively (Table 4). ARFN was not significantly affected by interaction between fertilizer N application rate and fertilizer N application date for any of the harvests in this study (Table 3.4).

Application date had a significant effect on ARFN in H1 and H4 but not H3 in 2005. Conversely application date had a significant effect on ARFN in H3 but not H1 and H4 in 2006. Where there were detectable differences between application dates (H4 in 2005 and H3 in 2006) the highest ARFN was associated with D2.

In both 2005 and 2006 application rate had no significant effect on ARFN at H1. At H3 in 2005 the highest ($P<0.001$) AFRN was with 30+30 application rate followed by 0+60, 30+60 and 0+90; i.e. application rates with a greater proportion of N in the later split. The lowest AFRN at H3 in 2005 was with application rate treatments where a greater proportion of N was applied in the earlier split. This trend was also clearly evident at the following harvest, H4 in 2005 and was evident, albeit less clearly so, in H4 in 2006 although that there was no significant difference between application rates at H4 in 2006.

Table 3.4 The effects of fertilizer application rate, fertilizer N application date and harvest date (see Table 3.1) on apparent recovery of fertilizer N (ARFN kg/kg of applied fertilizer N) during the spring in 2005 and 2006 (data from both sites averaged in each year)

Year:	2005				2006			
Harvest date:	H1	H2	H3	H4	H1	H2	H3	H4
Application rate (R)								
0+60			0.56	0.67			0.23	0.56
0+90			0.52	0.57			0.24	0.54
30+30	0.25		0.65	0.61	0.10		0.34	0.61
30+60	0.23		0.52	0.59	0.08		0.29	0.52
60+0	0.19		0.48	0.44	0.05		0.33	0.57
60+30	0.17		0.46	0.47	0.06		0.32	0.54
90+0	0.15		0.47	0.44	0.04		0.28	0.46
SEM	0.029		0.026	0.030	0.020		0.023	0.040
Application date (D)								
D1	0.21		0.55	0.38	0.05		0.29	0.51
D2	0.12		0.51	0.68	0.07		0.35	0.62
D3	0.31		0.52	0.60	0.09		0.24	0.49
D4	0.15		0.51	0.51	0.06		0.29	0.55
SEM	0.037		0.032	0.035	0.029		0.023	0.037
Level of significance								
Rate	NS		***	***	NS		**	NS
Date	**		NS	***	NS		**	NS
R x D	NS		NS	NS	NS		NS	NS

*, P<0.05; **, P<0.01; ***, P<0.001, NS, Non-Significant.

3.4.5 Fertilizer N application dates and grass production

The application of fertilizer N, applied at rates of 60 or 90 kg/ha, on each of eight dates between 11 January and 14 March, in more instances than not, date had no detectable (P>0.05) impact on grass DM production (Table 3.5). In instances where application date did have a significant (P<0.05) effect, the R^2 of grass DM production response to fertilizer N input tended to be low with a mean value of approximately 0.30.

With the input of 60 kg/ha of fertilizer N at Moorepark application date had a significant impact on grass production for H2 and H3 in 2006 both of which indicated that earlier application of fertilizer N resulted in higher grass DM yields. For the other harvests there was no significant effect.

Similarly, with the input of 60 kg/ha of fertilizer N at Solohead application date had a significant impact on grass production for H2 and H4 in 2005 along with H2 and H3 in 2006. However, these relationships indicated a trend at Solohead for intermediate or later application dates giving greater grass production responses.

With the input of 90 kg/ha of fertilizer N at Moorepark application date had a significant ($P<0.05$) or close the significant impact on grass production on all harvest dates in 2005 and 2006 except H4 in 2006. The trend was for later application dates to give greater grass DM production for H3 and H4 in 2005. In contrast, earlier application dates resulted in greater grass DM production for H2 in 2005 and H3 in 2006.

With the application of 90 kg/ha at Solohead an earlier application date resulted in greater grass DM yields in H1 and H2 in 2005. On the other hand, a later application date gave a higher grass production response at H4 at Solohead in 2005. With the input of 90 kg/ha of fertilizer N at Solohead application date had no significant impact on grass yields in 2006, albeit close to significance for H1 and H2 (Table 3.5).

Table 3.5 Best fit response curves of grass dry matter (DM; kg/ha) yield harvested on four dates in spring to single applications of 60 and 90 kg/ha of fertilizer N applied on eight dates (see Table 3.1) between 11 January and 14 March 2005 and 2006.

Year	Harvest	Intercept	b[‡]	c[‡]	R^2	Significance	Intercept	b	c	R^2	Significance
				Moorepark					Solohead		
						Fertilizer N 60 kg/ha					
2005	**H1**	835	-3.16		0.115	NS	532	0.81		0.004	NS
2005	**H2**	1242	-5.94		0.424	NS	933	6.85	-0.203	0.453	<0.001
2005	**H3**	2060	-3.85		0.109	NS	1732	-2.6		0.029	NS
2005	**H4**	3240	0.37		0.000	NS	2530	6.54		0.188	0.034
2006	**H1**	324	6.21	-0.147	0.107	NS	199	15.35	-0.282	0.109	NS
2006	**H2**	470	-1.86		0.273	0.004	416	8.19	-0.147	0.243	0.031
2006	**H3**	1366	-7.33		0.294	<0.001	661	26.46	-0.346	0.226	0.006
2006	**H4**	2421	-1.17		0.004	NS	2410	-3.1		0.018	NS
						Fertilizer N 90 kg/ha					
2005	**H1**	839	7.19	-0.261	0.315	0.056	720	-6.33		0.377	0.032
2005	**H2**	1447	-9.58		0.548	<0.001	950	-4.53		0.245	0.022
2005	**H3**	2219	5.88	-0.164	0.455	<0.001	1846	-0.58		0.001	NS
2005	**H4**	3483	3.77	-0.124	0.211	0.033	2615	9.96		0.185	0.035
2006	**H1**	349	6.26	-0.167	0.244	0.050	283	14.27	-0.364	0.228	0.061
2006	**H2**	498	-1.68		0.106	0.091	481	-1.82		0.139	0.055
2006	**H3**	1488	-8.42		0.303	<0.001	999	11.55	-0.165	0.106	NS
2006	**H4**	2467	23.4	-0.351	0.134	NS	2495	-1.6		0.008	NS

[‡]b and c are quadratic and linear coefficients, respectively; NS, Non-significant.

3.4.6 DM grass production and economic performance

The second application date combination (21 Jan and 26 Feb) gave the best value for money and this was more clearly identifiable in 2005 than 2006 (Figure 3.2)

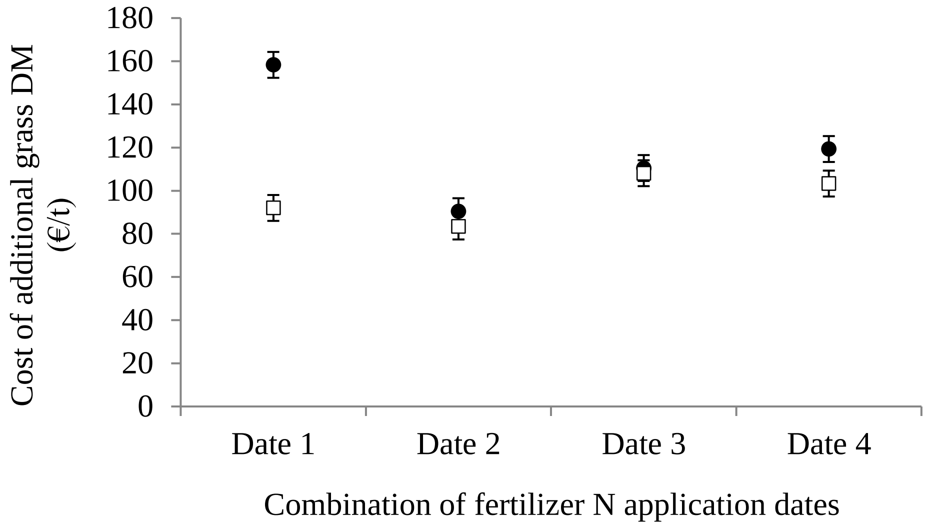


Figure 3.2 Economic cost (€/t DM) of grass harvested on 25 April following the application of fertilizer N on four date combinations (see Table 1) in 2005 (●) and 2006 (□) at both sites. $P < 0.01$; Error bar = ±standard errors of means.

Overall the treatment that offered the best value for money in terms of additional grass DM grown as a consequence of fertilizer N application was the 30+60 treatment (Figure 3.3).

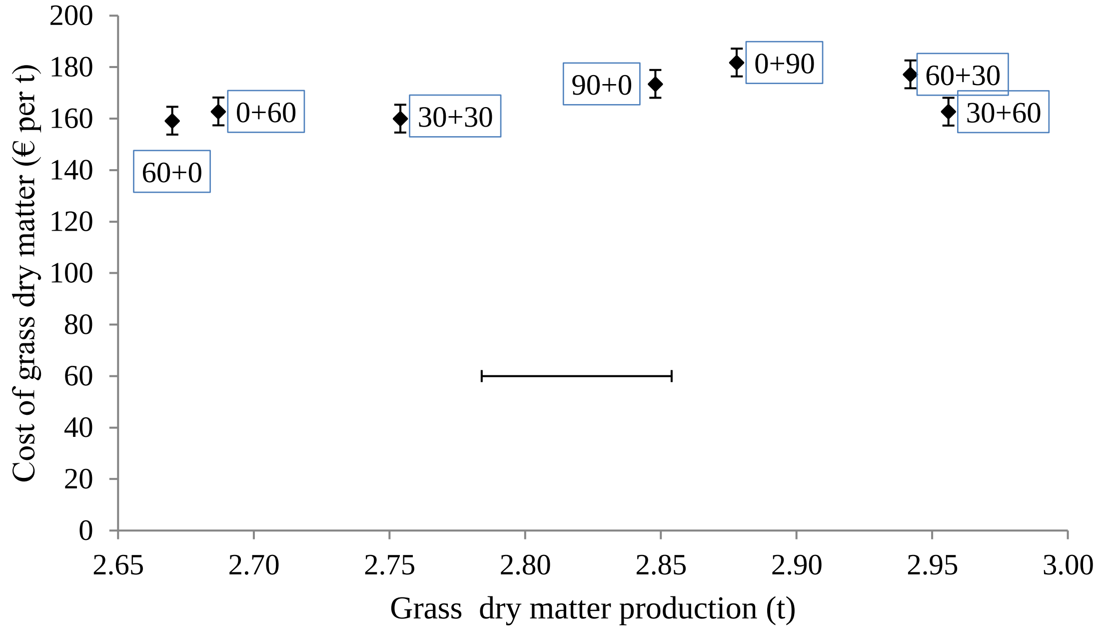


Figure 3.3 Grass dry matter production and the cost of growing the additional grass (€ per t DM) above that produced with no fertilizer N input. Vertical error bars are ± standard errors of means for costs (€) per t DM and the horizontal error bar is the standard errors of means for grass DM production.

3.5 Discussion

3.5.1 Weather conditions

In 2005 accumulated rainfall from 1 January to 30 April was within 3% of the long term average for both Moorepark (316 vs. 326 mm) and Solohead (318 vs. 330 mm). In 2006 there was less rainfall at both sites with 247 mm at Moorepark (25% below average) and 225 mm at Solohead (32% below average).

During the same timeframe in 2005 soil temperatures at 10 cm depth were approximately 0.4°C and 0.2°C above average at both Moorepark and Solohead being 7.4°C and 6.7°C, respectively. In 2006 soil temperatures were close to average at Moorepark but below average at Solohead (5.6°C vs. 6.5°C). The weather during the experimental period was milder and wetter in 2005 in comparison with 2006. As a result 2005 provided weather conditions which were much more conducive, in particular at the earlier harvest dates, for grass DM production, herbage N uptake and ARFN (Table 3.2, 3.3 and 3.4).

3.5.2 Date of application

More often than not the date on which fertilizer N was applied had no significant effect on DM grass production (Table 3.2 and 3.5). Where an effect was detected the results were often conflicting with all four fertilizer N application dates having the potential to give increased grass DM yields depending on year, site and rate of fertilizer N application. This is probably not surprising bearing in the mind the differences in weather conditions between the two years and the differences in soil type and elevation (50 m versus 150 m ASL) between the two sites. In the instances where significant effects were detected only about 30% of the variation in grass production was attributable to application date and, hence, other factors made a much greater contribution towards variation in DM yield (Table 3.5). Other studies have also found a lack of a clearly identifiable optimum date for fertilizer N application in spring (Stevens *et al*. 1989; Long *et al.* 1991; Laidlaw *et al*. 2000), which is in contrast to O'Donovan *et al*. (2004) who concluded, based on an experiment conducted at Moorepark, that the optimum date for the application of fertilizer N in spring was in early January for the south west of Ireland.

In the present study, there was a trend for earlier application dates to give improved grass production at the earlier harvest dates during the milder spring of 2005, particularly at Moorepark. In Ireland, fertilizer N in spring is often typically applied in anticipation of expected growth, which is based on average weather conditions and grass growth rates in previous years. Therefore, when looked at solely from the perspective of anticipated growth, it can often make sense to apply fertilizer N on an earlier application date (Humphreys, 2007). Since the introduction of the Nitrates Directive in Ireland in 2006 there is greater recognition of the need to limit losses from the production system. In the present study, ARFN at H4 indicated the extent of N uptake in grass DM (Table 3.4) and in 2005 the earliest date combination had the poorest ARFN and the second date had the highest. There was a similar trend at H3 in 2006, whereas application date had no significant effect on ARFN at H4 in 2006. This is also reflected in the economic response to fertilizer N, where the most cost effective option was the application of fertilizer N on the second application date combination (21 Jan and 26 Feb; Figure 3.2), particularly in 2005. In this instance there was good agreement between cost-effectiveness and ARFN.

Part of the reason for the poorer ARFN with the later application date application combinations (D3 and D4) was due to later application dates; probably not all of the applied fertilizer N had been taken up by the crop by the time of the final harvest on 25 April (H4). It is likely that if the timeframe of this study was extended beyond 25 April, that higher ARFNs' would have been recorded for the later application date combinations similar to that recorded by Murphy *et al*. (2013). However, such considerations are outside the scope of this study, which was focused on the timeframe between 21 February and 25 April, which approximately coincides with the typical calving interval of spring-calving herds in Ireland; when cows are turned out to pasture after calving. The economic consideration in the present study is the feed and other costs associated with keeping cows indoors on grass-silage and concentrates or turning the cows out to grazed-grass. O'Donovan *et al*. (2011) put a cost on grass silage of €183 per t of utilizable DM and €230 per 1000 UFL and concentrate cost in recent years averaged €325 per t DM (assuming 85% DM content) according to CSO (2018). The costs of these alternative feeds are substantially higher than the cost of additional grass grown as a consequence of fertilizer N application (Figures 3.2 and 3.3). This comparison does not account for the poorer nutritive value of grass-silage compared to grazed grass in spring or the other costs of keeping cows indoors such as cost of feeding, bedding and slurry application. In the present study it is clear that the application of fertilizer N in spring offered a substantially lower cost option for feeding dairy cows within the timeframe relative to alternatives regardless of the fertilizer N application date and application rate treatments imposed.

However, of the application date treatments imposed the second application date combination (21 January and 26 February) was probably the best option in terms of cost effectiveness and ARFN.

3.5.3 Rate of application

Fertilizer N was applied at two rates in this study: 60 kg/ha and 90 kg/ha; and in single or combined (split) applications. In general, the biggest differences in grass yields were between treatments that had received fertilizer N and those that did not and this was evident across harvest dates including the earliest harvest date (H1). In general there was no difference in grass yields between applications of 30 kg/ha, 60 kg/ha or 90 kg/ha. The exception to this was H2 in 2005, when the earlier applications at higher rates (60 kg/ha and 90 kg/ha) gave a higher grass production response compared with where 30 kg/ha was applied. On the other hand earlier applications at higher rates tended to be lower yielding at later harvest dates, particularly in 2005. Furthermore, ARFN tended to be higher with lower rates of application, for later application dates and for split applications (30+30) and (30+60), particularly when a greater proportion of applied fertilizer N was in the later split.

The timeframe of the harvests in this experiment were set up to coincide with the first grazing rotation on many dairy farms in southern Ireland. From late April onwards grass growth generally exceeds demand for grazed grass and this excessive supply means that grazed grass becomes relatively less valuable throughout the spring; i.e. it no longer has the same value relative to grass-silage and concentrates as described above. On this basis it can be argued that additional grass at H1 was more valuable than additional grass at H4. It is also likely that a deficit in supply of grazed grass can occur at any stage during the first grazing rotation depending primarily on the impact of weather conditions on grass growth, which are very variable from year to year (Figure 3.1). Indeed a shortage of grazed grass can often be most acute and problematical towards the end of the first grazing rotation in years with poorer grass growing conditions within this timeframe. Hence, for simplicity grazed grass is valued equally within the timeframe of this experiment. The additional grass harvested at H4 was accumulated during the timeframe of the experiment and, hence, the cost of additional grass DM produced is taken as indicative of each treatment (Figure 3.3). In general, the split applications of fertilizer N (30+30) and (30+60) were the most cost effective treatments for the quantity of applied fertilizer N (Figure 3.3).

3.6 Conclusion

Grass DM production increased with higher input of fertilizer N and split applications (30+30) and (30+60) tended to produce higher grass DM production than single applications for both levels of fertilizer N input (60 kg/ha and 90 kg/ha) in this study. Split applications also resulted in higher ARFN, particularly where a greater proportion of applied fertilizer N was in the later split. The optimum date to commence fertilizer N application was 21 January combined with a second application on 26 February in terms of the cost effectiveness of the fertilizer N input to increase grass DM production. Earlier application dates increased grass DM production when conditions were suitable. On the other hand, earlier application dates resulted in a poor grass DM production response when conditions were not suitable and were also associated with lower ARFN. Taking into account the variability of weather and grass growing conditions from year to year in spring a low level of fertilizer N input (30 kg/ha) is recommended in early spring when the grass DM production response can be variable and risks of losses are high. This should be followed by a second application later in the spring when there is likely to be higher recovery of applied fertilizer N and higher grass DM production response.

Chapter 4 Effects of fertilizer-N application at different regrowth stages on grass production

4.1 Abstract

In grassland it is typically recommended that fertilizer N is applied immediately after defoliation in each grazing/cutting rotation throughout the year. In practice, farmers often deviate from this approach with a 'blanket' approach on farms where fertilizer N is applied once per rotation; i.e. fertilizer N is applied to swards at different stages of regrowth across the farm. A study was conducted at two sites with different soil types (sandy loam and clay loam) in Ireland in 2004 and 2005. Fertilizer N was applied on 24 occasions throughout each growing season. There were three sets of plots at each site with each set receiving applications of fertilizer N eight times and harvested eight times per year. Fertilizer N application to each set was offset by approximately 10 days following the start of the experiment each spring with overlapping harvests of each set throughout each growing season. Two fertilizer N application strategies were compared: (i) application immediately after each harvest (IAH) in each rotation and (ii) a blanket application once per rotation, which was represented by the mean outcome of fertilizer N applied at different stages of regrowth (SOR): IAH, early to mid-rotation (EM) and mid to late rotation (ML). Two types of fertilizer N; Calcium ammonium nitrate (CAN) and urea were applied at annual rates of 200 and 300 kg N/ha. Treatments in this three factor experiment (SOR x fertilizer type x fertilizer rate) were arranged in a randomized complete block design with three replications per site. Swards were harvested at four week intervals until mid-August, at five week intervals until mid-September and at six to eight week intervals for harvests from mid-October to late November. Fertilizer application strategy, type and rate all had a significant ($P \leq 0.001$) effect on grass dry matter (DM) production. CAN produced higher annual DM yields than urea and differences were greatest during the spring and early summer. Applying fertilizer IAH produced the highest DM yields except where urea was applied at a rate of 300 kg N/ha. A blanket approach to fertilizer N application can be integrated into an annual fertilizer N application strategy between mid-January and mid-March and from July onwards with little or no loss of production provided that fertilizer N is applied IAH at the other time of the year.

Keywords: calcium ammonium nitrate, fertilizer N application, grass DM production, stage of re-growth, urea.

4.2 Introduction

The strategic use of fertilizer N is regarded as the central component of grassland management (Humphreys *et al*. 2003a). Fertilizer N management needs to consider grass dry matter (DM) production, cost-effectiveness and potential damage to the environment. Fertilizer N application on farms involves labour and energy inputs, with the frequency of application being directly related to the cost-effectiveness of grassland management (Ferris *et al*. 2008). A study of fertilizer N application practices on intensive dairy farms in the southwest of Ireland indicated that, from mid-January through to mid-September, the number of times that individual farmers applied fertilizer N ranged from eight occasions per year to 85 occasions per year (Treacy, 2008). The former approach represents what is known as a 'blanket' approach (BL), where fertilizer N is applied to the entire farm area on one occasion per defoliation (typically grazing) rotation and the latter represents an 'immediately after harvest' (IAH) approach to fertilizer N application. With blanket N application the fertilizer N is applied to paddocks that are at different stages of regrowth (SOR) within a gazing rotation (Brockman, 1974). One important question is whether there exists an optimum SOR for N application within a grazing rotation in order to optimise grass DM production while reducing N losses to the environment. Is it IAH or at some other point during the following interval of re-growth? With blanket application fertilizer N is applied to swards at varying stages of regrowth and, as such, may result in possible detrimental effects on the productivity of grassland, on N use efficiency and, hence, on the environment.

A study in Northern Ireland indicated that there was no significant difference in the performance of dairy cows in a pasture-based system when calcium ammonium nitrate (CAN) was applied either immediately after grazing (within two or three days) or by (infrequent) blanket application in terms of total milk output per ha, average daily milk yield per cow, milk fat and protein concentrations, final live weight, body condition score, milk urea and plasma urea concentrations (Ferris *et al*. 2008). However, the latter study did not directly quantify grass DM production. The application of N at different SOR can affect chemical composition, in particular N concentration in grass DM (Wilman, 1975; Wilman and Wright, 1983). For example, a study conducted in Northern Ireland (Watson, 1986b) showed that fertilizer N applications a week prior to harvest elevated N concentrations in grass DM with negative implications for N use efficiency. Thus, there is a concern with applying fertilizer N at different SOR because even if there is no determinable difference in animal production performance, there still is uncertainty surrounding the impact on grass DM production and rates of recovery of applied fertilizer N by the grass crop, which have economic and environmental implications.

CAN (27.5% N) and urea (46% N) are the two most widely used forms of straight fertilizer N in Ireland (Lalor *et al*. 2010). Urea is less expensive than CAN per kg of N, although CAN represents a much higher proportion (88%) of fertilizer N sales in Ireland (CSO, 2018). Urea is generally recommended for application to grassland in Ireland during the spring (until the end of May) and subsequently, during summer and early autumn it is recommended to use CAN (Humphreys, 2007). This is because the N in urea is believed to be much more susceptible to loss through volatilization of ammonia during warmer and drier periods of the year (Watson *et al*. 1992b). For example, mean cumulated ammonia loss from grassland receiving CAN may be up to 85% lower than urea and are also highly variable (range 10 to 58%) for urea (Chambers and Dampney, 2009; Forrestal *et al*. 2015) The extent of volatilization of N in urea is higher on exposed soil surfaces with low sward cover compared to where there is a well-developed, dense canopy, since some of the volatilized ammonia is trapped in the foliage and re-used by the plant (Pain *et al*. 1998; Ping *et al*. 2000). A second objective of this study was to determine whether applying urea to a well-developed grass canopy could improve N recovery by the sward and grass productivity in comparison with urea applied to bare stubble IAH. In this study, either CAN or urea was applied to grass at different SOR for swards harvested on eight occasions throughout the growing seasons of two years. The results are used to identify the most appropriate fertilizer N application strategies to be used throughout the entire grass growing season.

4.3 Materials and Methods

4.3.1 Experimental site characteristics

The experiment was conducted at the Teagasc Animal and Grassland Research and Innovation Centre at Moorepark (50°09'N, 08°15'W; altitude 50 m a.s.l.) and at the Teagasc Solohead Research Farm (52°51'N; 08°21'W; altitude 150 m a.s.l.) in 2004 and 2005. The soil at Moorepark is classified as a free-draining acid brown earth soil of sandy loam to loam texture. Soil pH, total N and total C content in the surface 10 cm of soil were 6.5, 0.48% and 4.48%, respectively. The site is seasonally dry and drains quickly in periods of high rainfall.

The soil at Solohead is classified as poorly drained gleys (90%) and grey-brown podzolics (10%) with a clay loam texture. Soil pH, total N and total C content in the surface 10 cm of soil were 6.5, 0.54% and 5.35%, respectively. The site is seasonally wet and water logged during periods of high rainfall. The local climate at both sites is maritime in nature and there is a long potential growing season ranging from 270 to 300 days (Brereton, 1995).

At Solohead, meteorological data were recorded as described by Fitzgerald and Fitzgerald (2004), while at Moorepark meteorological data were recorded on an hourly basis at an on-site automatic weather station from the Irish Meteorological service (Met Eireann).

4.3.2 Experimental layout and design

This study was conducted at both sites in 2004 and 2005. Prior to this study, the swards at both sites had been renovated in the late 1990's and were comprised of perennial ryegrass (*Lolium perenne L. cv.* Magella) and had been since used for pasture based dairy production. A soil test in advance of the study indicated no requirement for the application of lime and that phosphorous (P) and potassium (K) levels were adequate. Nevertheless, throughout the study basal rates of P and K were applied by hand in the form of a 0:7:30 PK granular compound fertilizer (7% P & 30% K) to ensure soil P and K concentrations were not restricting grass growth (Table 4.1).

The experiment included a factorial arrangement of treatments laid out in a randomized complete block design with three replications at each site. Factors were (i) application of fertilizer N at three SORs (described below), (ii) two types of fertilizer N (CAN and UREA) and (iii) two annual rates of fertilizer N application: 200 kg/ha (N200) and 300 kg/ha (N300). The SORs were (i) immediately after harvest (IAH), early to mid-rotation (EM) and mid to late rotation (ML). Furthermore, harvest treatments were imposed using the same methodology as described by Corrall and Fenlon (1978); i.e. initial applications of fertilizer N (Table 4.1) and subsequent harvests were staggered at approximately 10-day intervals with overlapping harvests throughout the growing season. The latter approach was adopted to mitigate the potential effect of weather conditions on N availability to plants following application of fertilizer N. Fertilizer N was applied by hand in the form of fine crystalline solid of urea (46% N) or granular CAN (27.5% N). There were 36 plots (9 m x 0.9 m) per replicated block and a total of 108 plots per site each year. There was a 0.1 m wide buffer zone between each plot and a 4 m border surrounded each block. There was a total of 24 harvest dates each year. The initial harvest of grass each year took place in early March. From mid-March plots were harvested at four week intervals until mid-August. Grass was subsequently harvested at five week intervals until mid-September and at six to eight week intervals in October and November.

Table 4.1 Dates and rates of applications of fertilizer N and P & K compound fertilizer. Fertilizer N was applied at annual rates of 200 kg/ha (N200) and 300 kg/ha (N300).

Round	Application date			Fertilizer N (kg/ha)		7:30 fertilizer (kg/ha)	
				N200	N300	P	K
1	31 Jan	18 Feb	28 Feb	20	25	11.4	48.6
2	7 Mar	18 Mar	28 Mar	20	25	22.8	97.2
3	5 Apr	14 Apr	24 Apr	30	50	22.8	97.2
4	3 May	12 May	21 May	45	60	22.8	97.2
5	30 May	8 Jun	17 Jun	30	50	11.4	48.6
6	27 Jun	6 Jul	17 Jul	20	40	11.4	48.6
7	4 Aug	15 Aug	25 Aug	20	30	11.4	48.6
8	29 Aug	9 Sept	19 Sept	15	20	11.4	48.6

4.3.3 Grass sampling and laboratory analysis

At each harvest a strip 0.55m wide was cut from the centre of each plot along its full length to a height of approximately 4 cm using a Honda rotary blade lawnmower (HRH 535; Honda, Swepsonville, NC, USA). The harvested grass was collected and weighed and a sub-sample was taken for laboratory analysis. The grass on the remaining area of each plot was cut in the same way and discarded.

In the laboratory, a sub-sample of 100g of grass from each plot was dried for 16 h at 98°C in a forced air oven to a constant weight for the determination of DM content. For N analysis, a second sub-sample of 100g was dried in a forced draught oven at 40°C for 48 hours, and then milled to pass a 2mm sieve. The concentration of N in grass from the N300 treatments plots was determined by a LECO 528 auto analyzer (LECO Corporation, St. Joseph, MI, USA). N uptake was calculated by multiplying the grass DM yield by N concentration in harvested grass DM.

4.3.4 Costs of grass production

Ferris *et al*. (2008) assessed the amount of labour associated with both of the above fertilizer N application strategies. It was on the basis of a one hundred cow dairy herd and entailing a fertilizer spreading duration spanning 26.3 weeks between 15 March and 15 September. The lengths of time per week were 107 minutes for IAH and 83 minutes for BL.

In the present study the cost of labour per hour was €17. The cost of a kg of N in the form of CAN and urea were €1.09 and €0.85, respectively, based on a ten year average from 2008 to 2017 (CSO, 2018). Other costs associated with the production of a tonne (t) of grass DM included the cost of land rental (or the opportunity cost of land), reseeding, lime and P & K used. These were estimated to be €350/ha, €600/ha, €12/ha, €2.55/kg and € 0.78/kg, respectively (Finneran, 2010; Shalloo, 2011; CSO, 2017; Teagasc Pocket Manual, 2017).

4.3.5 Statistical analysis

Daily grass DM production for each combination of fertilizer type and application rate was subjected to ANOVA to examine the impact of SOR on annual-average daily grass DM production and grass DM production at each harvest date in both years using MSTAT (Freed *et al*. 1989). The main factors included the three SOR and 24 harvest dates at two sites in two years with three replications at each site in each year. Harvest date was included as a repeated measure in the model. Likewise N concentrations in grass DM and N uptake in grass DM for each of the N300 treatments were subjected to ANOVA to examine the impact of SOR over 22 harvest dates, which were included as a repeated measure in the model. The last two harvest dates were excluded from analysis due to the absence of laboratory results.

Daily grass DM production for each combination of fertilizer type and application rate was subjected to ANOVA to examine the impact of fertilizer N application strategy (IAH and BL, BL being the mean grass DM production of IAH, EM and ML as swards in a rotational system contain a comparable proportion of each of these three stages at the time of N application) on annual-average daily grass DM production and grass DM production at each harvest date at two sites in two years with three replications at each site in each year. Harvest date was included as a repeated measure in the model. Likewise N concentrations in grass DM and N uptake in grass DM for each of the N300 treatments were subjected to ANOVA to examine the impact of application strategy over 22 harvest dates, which were included as a repeated measure in the model. The last two harvest dates were excluded from analysis due to the absence of laboratory results.

Daily grass DM production was subjected to ANOVA to examine the impact of fertilizer N application strategy (IAH and BL) examining the main effects of each factor (application strategy x fertilizer type x application rate) and interaction between factors.

4.4 Results

4.4.1 Weather conditions

Weather conditions at both sites in 2004 were fairly similar to the 20-year average, whereas 2005 tended to be drier and warmer than average (Table 4.2). In 2004 total annual rainfall in Moorepark was 1032 mm compared with the long-term average of 1044 mm. At Solohead rainfall in 2004 was 1000 mm compared with a long-term average of 1071 mm. In 2005 there was less rainfall at both sites, particularly at Solohead: 1028 mm at Moorepark and 885 mm at Solohead.

Table 4.2 Averaged daily soil temperature (°C) each month at a depth of 10 cm and monthly rainfall (mm) at Solohead and Moorepark in 2004 and 2005.

	Solohead		Moorepark	
	2004	2005	2004	2005
Soil temperature (°C)				
Jan	4.6	6.1	5.5	6.3
Feb	4.9	5.0	3.5	5.3
Mar	5.7	7.1	7.0	7.9
Apr	8.6	8.5	9.6	9.7
May	11.6	11.4	14.1	11.9
Jun	15.7	15.7	17.6	17.4
Jul	15.1	16.8	17.3	18.6
Aug	16.1	16.1	17.5	17.7
Sep	14.2	14.2	14.5	15.5
Oct	9.4	11.6	10.1	12.5
Nov	8.5	7.5	8.8	8.5
Dec	6.6	5.8	6.8	6.8
Mean	**10.1**	**10.5**	**11.0**	**11.5**
Monthly rainfall (mm)				
Jan	99.5	122.7	102.5	119.8
Feb	36.8	55.9	56.8	34.8
Mar	78.4	62.3	112.4	79.4
Apr	57.8	77.3	64.5	82.2
May	53.3	56.0	42.9	74.7
Jun	58.2	32.0	89.3	82.4
Jul	35.3	57.1	46.6	66.9
Aug	161.8	49.2	171.1	47.8
Sep	87.0	87.7	79.0	104.6
Oct	186.4	128.2	170.4	153.4
Nov	53.6	91.9	27.2	105.6
Dec	92.1	65.1	68.9	75.5
Total	**1000**	**885**	**1032**	**1028**

In 2004 soil temperatures at 10 cm depth were slightly cooler (-0.1°C) than average for both Moorepark and Solohead (Table 2). In 2005 soil temperatures at 10 cm depth were warmer (+0.4°C) than average at Moorepark and (+0.3°C) at Solohead

4.4.2 Application of fertilizer N at different stages of regrowth (SOR)

4.4.2.1 Grass production, N concentration and N uptake in grass DM

The application of fertilizer N at different SOR had an impact on annual-average daily grass growth rates for CAN300 ($P<0.001$), CAN200 ($P<0.001$) and UREAN200 ($P<0.001$) but not UREAN300 (Table 4.3). In general, where there were significant differences between SOR, IAH resulted in the highest DM grass production followed by EM and then by ML. For each of the fertilizer N type and rate treatments there were interactions between SOR and year, with the difference between IAH and the other two SOR treatments much more evident in 2004 than 2005; in general differences in grass growth rates between SOR treatments were insignificant or small in 2005.

Furthermore the impact of SOR treatments on grass DM growth rates differed during the course of the growing season (Figure 4.1). For CAN300 (Fig 4.1A) and CAN200 (Fig 4.1C) IAH generally had higher grass DM growth rates than the other two SOR treatments for harvests between mid-April and late August and not at other times of the year. There was a similar but less obvious trend for UREAN200 and, in line with annual-average daily grass growth rates, little or no differences between SOR at different dates during the growing season for UREAN300.

The application of 300 kg/ha of fertilizer N (CAN300 and UREAN300) at different SOR had a significant effect ($P\leq0.001$) on N concentration in grass DM (Fig 4.2A & Fig 4.2B). In general the highest concentrations were for ML followed by EM and lowest concentrations associated with IAH. Concentrations also varied during the growing season; being highest early and late in the season and lowest during mid-season.

With both fertilizer types the highest N uptake in grass DM was by ML, followed by EM and then by IAH although differences between there SOR treatments were small or insignificant during the course of the growing season (Fig 4.3C & 4.3D).

Table 4.3 Daily DM yields (kg/ha) where fertilizer N was applied at different stages of regrowth (SOR): Immediately after each harvest (IAH); Early to mid-rotation (EM); Mid to late-rotation (ML).

			CAN 300			
Site (S)		Moorepark			Solohead	
SOR	IAH	EM	ML	IAH	EM	ML
2004	57.6	53.3	53.2	54.3	50.8	50.1
2005	46.5	45.6	46.5	42.7	42.9	41.9
Mean	52.1	49.5	49.9	48.5	46.9	46.0
			SEM			SEM
		SOR	0.304***		SOR x S	0.430 NS
		Site (S)	0.248***		SOR x Y	0.430***
		Year (Y)	0.248***		S x Y	0.351 NS
			UREA 300			
Site (S)		Moorepark			Solohead	
SOR	IAH	EM	ML	IAH	EM	ML
2004	50.8	50.1	49.0	49.0	46.6	46.6
2005	45.4	46.0	47.1	41.5	43.1	40.1
Mean	48.1	48.1	48.1	45.2	44.8	43.3
			SEM			SEM
		SOR	0.366 NS		SOR x S	0.518 NS
		Site (S)	0.299***		SOR x Y	0.518*
		Year (Y)	0.299***		S x Y	0.423*
			CAN 200			
Site (S)		Moorepark			Solohead	
SOR	IAH	EM	ML	IAH	EM	ML
2004	50.4	46.9	45.0	48.6	45.7	43.3
2005	44.3	44.1	41.0	42.0	41.3	38.4
Mean	47.4	45.5	43.0	45.3	43.5	40.8
			SEM			SEM
		SOR	0.289***		SOR x S	0.409 NS
		Site (S)	0.236***		SOR x Y	0.409*
		Year (Y)	0.236***		S x Y	0.334NS

Table 4.3 continued

Urea 200						
Site (S)		Moorepark			Solohead	
SOR	IAH	EM	ML	IAH	EM	ML
2004	47.0	44.1	43.3	44.5	41.9	41.4
2005	44.5	43.6	41.5	39.0	40.8	37.8
Mean	45.8	43.8	42.4	41.7	41.4	39.6
			SEM			SEM
		SOR	0.366***		SOR x S	0.517 ^{NS}
		Site (S)	0.297***		SOR x Y	0.517*
		Year (Y)	0.297***		S x Y	0.422

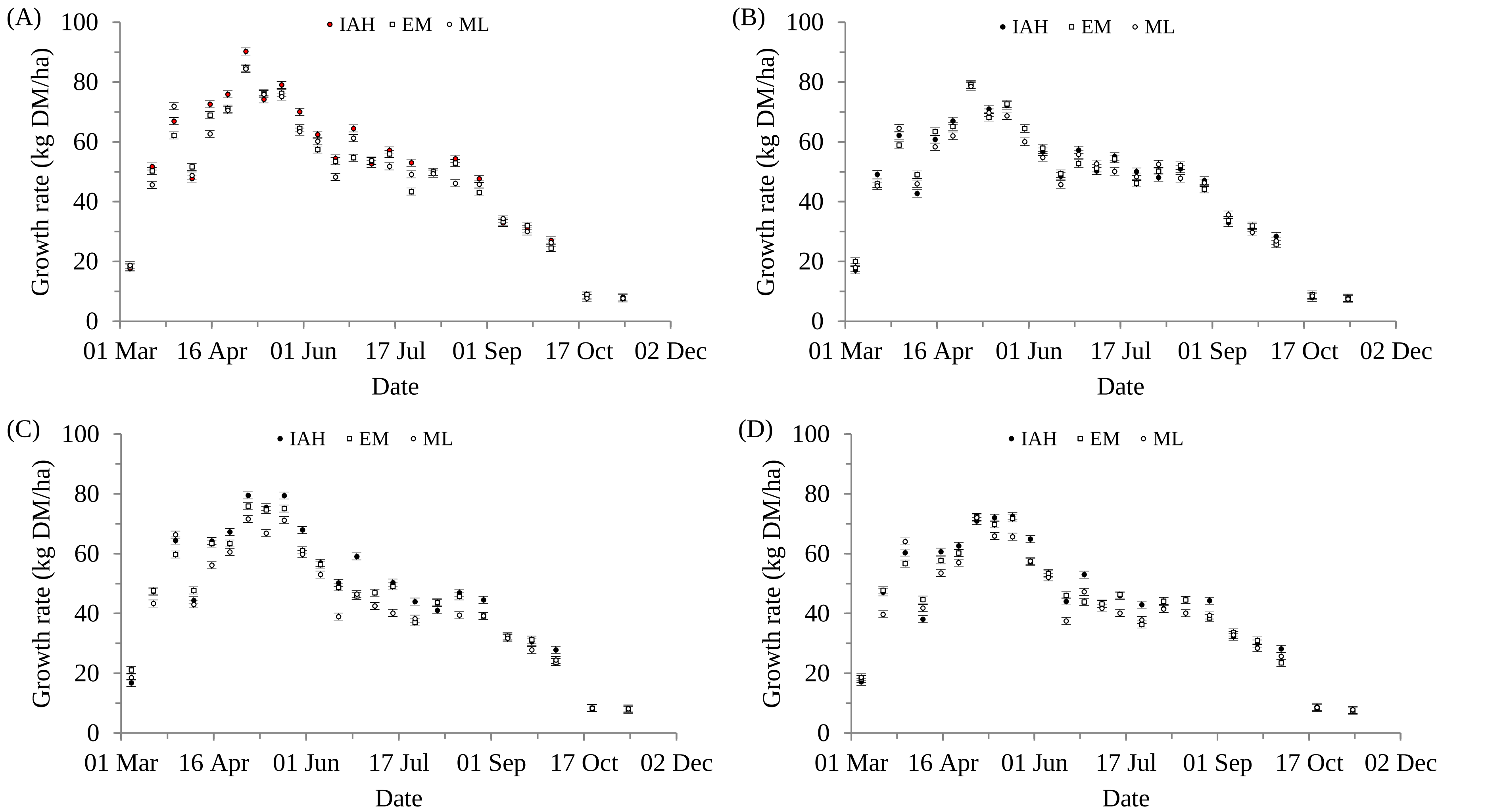


Figure 4.1 Daily growth rates (kg DM/ha) where fertilizer N was applied immediately after harvest (IAH), early to mid-rotation (EM) and mid to late-rotation (ML) for (A) CAN applied at a rate of 300 kg N/ha, (B) urea applied at a rate of 300 kg N/ha, (C) CAN applied at a rate of 200 kg N/ha and (D) urea applied at a rate of 200 kg N/ha. Data are the mean of three replications, two sites and two years.

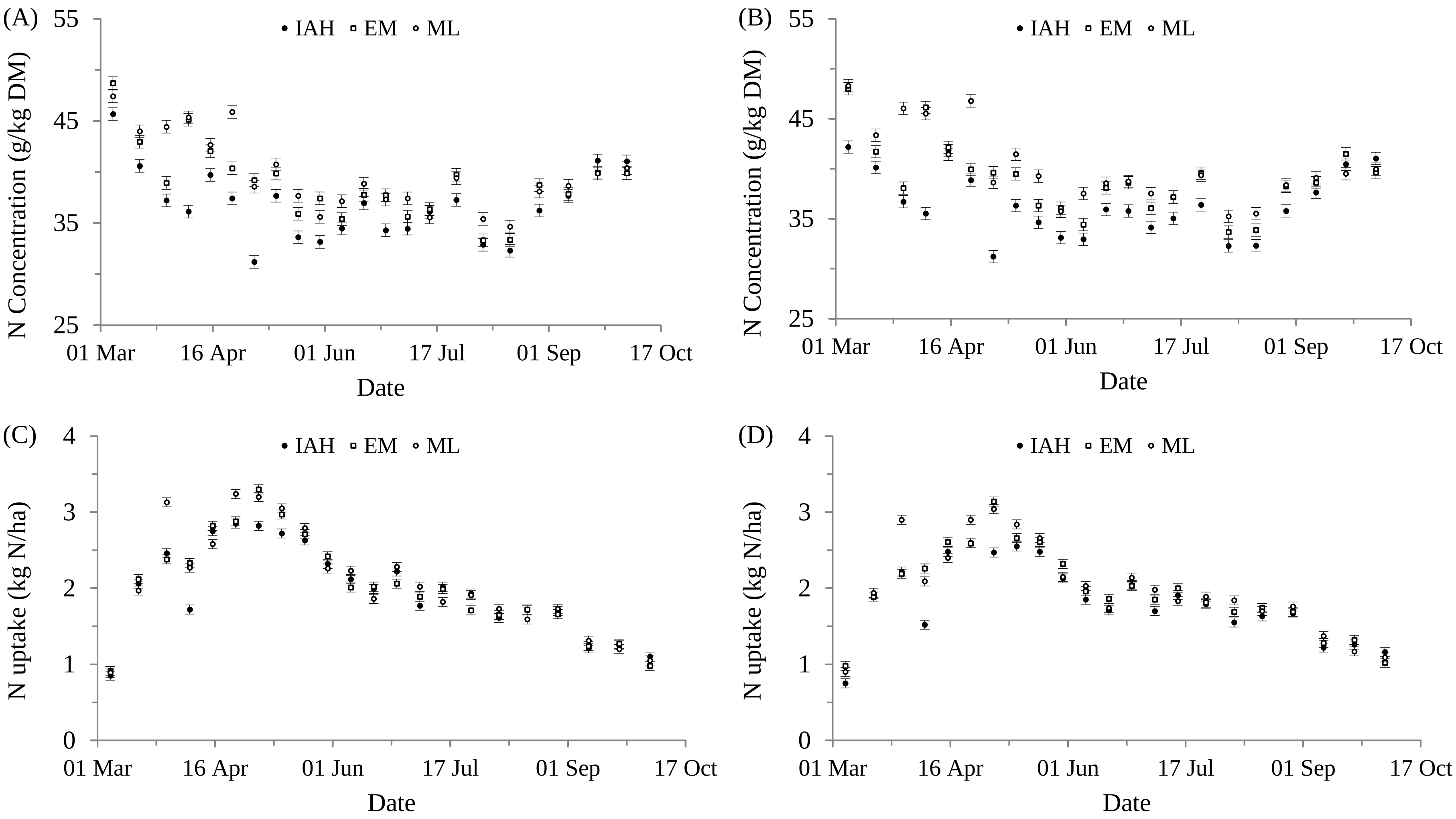


Figure 4.2 N concentration in grass DM (g/kg) and daily N uptake (kg/ha) where fertilizer N was applied immediately after harvest (IAH), early to mid-rotation (EM) and mid to late-rotation (ML) for (A) & (C) CAN applied at a rate of 300 kg N/ha and (B) & (D) UREA applied at a rate of 300 kg N/ha. Data are the mean of three replications, two sites and two years.

4.4.3 Fertilizer N application strategies

4.4.3.1 Grass production and N uptake in grass DM

When comparing the BL and IAH application strategies the IAH had higher annual-average daily grass DM growth rates than the BL strategy for CAN300 (P<0.001), CAN200 (P<0001) and UREAN200 (P<0.001) with no difference (P>0.05) between strategies for UREAN300 (Table 4.4). Similar to the SOR the differences in annual-average daily grass DM growth rates between application strategies were larger in 2004 than in 2005, when differences tended to be relatively small or insignificant.

Differences in daily grass DM growth rates between IAH and BL were somewhat similar to the differences in SOR presented above (Figure 4.3): biggest differences between strategies between CAN300 and CAN200 were observed between mid-April and the end of August; a similar but less pronounced trend for UREAN200 and no differences between daily grass DM growth rates at different dates during the growing season for UREAN300.

N uptake in grass DM followed a somewhat similar trend to grass growth rates during the growing season for CAN300 and UREAN300; where there were differences between application strategies, BL tended to have higher rates of N uptake (Figure 4.4).

Taking into account the differential in the costs between CAN and UREA and IAH and BL, strategies can be ranked in terms of costs as follows: UREA BL < UREA IAH < CAN BL < CAN IAH (see section 4.3.4 for costings). Furthermore, if we include the proviso that fertilizer N input is curtailed under Nitrates Directive Regulations necessitating maximum productivity per kg of N applied it is possible to determine the optimum combination of fertilizer type and application strategy at different times of the year (Table 4.5). For example, for fertilizer N applied on 31 January there was no difference in grass DM production between treatments and, hence, UREA BL is the optimum approach because it is the lowest cost option. On the other hand, for fertilizer N applied on the 5 April or 24 April, for example, CAN IAH is the optimum approach because it gave higher (P <0.001) grass DM production (Table 4.5)

Table 4.4 Daily grass dry matter (DM) growth rates (kg/ha) where fertilizer N was applied using two fertilizer strategies (FS): Immediately after each harvest (IAH) or using a Blanket (BL) application strategy.

CAN 300		Moorepark		Solohead
Site (S)	IAH	BL	IAH	BL
2004	57.6	54.7	54.3	51.7
2005	46.5	46.2	42.7	42.5
Mean	52.1	50.5	48.5	47.1
		SEM		SEM
	FS	0.173***	FS x S	0.245 NS
	Site (S)	0.173***	FS x Y	0.245**
	Year (Y)	0.173***	S x Y	0.245 NS
UREA 300		Moorepark		Solohead
Site (S)	IAH	BL	IAH	BL
2004	50.8	49.9	49	47.4
2005	45.4	46.2	41.5	41.5
Mean	48.1	48.1	45.3	44.5
		SEM		SEM
	FS	0.193 NS	FS x S	0.274 NS
	Site (S)	0.193***	FS x Y	0.274*
	Year (Y)	0.193***	S x Y	0.274**
CAN 200		Moorepark		Solohead
Site (S)	IAH	BL	IAH	BL
2004	50.4	47.4	48.6	45.9
2005	44.3	43.1	42.0	40.6
Mean	47.4	45.3	45.3	43.3
		SEM		SEM
	FS	0.186***	FS x S	0.264 NS
	Site (S)	0.186***	FS x Y	0.264*
	Year (Y)	0.186***	S x Y	0.264 NS
UREA 200		Moorepark		Solohead
Site (S)	IAH	BL	IAH	BL
2004	47	44.8	44.5	42.6
2005	44.5	43.2	39	39.2
Mean	45.8	44.0	41.8	40.9
		SEM		SEM
	FS	0.140***	FS x S	0.198*
	Site (S)	0.140***	FS x Y	0.198**
	Year (Y)	0.140***	S x Y	0.198***

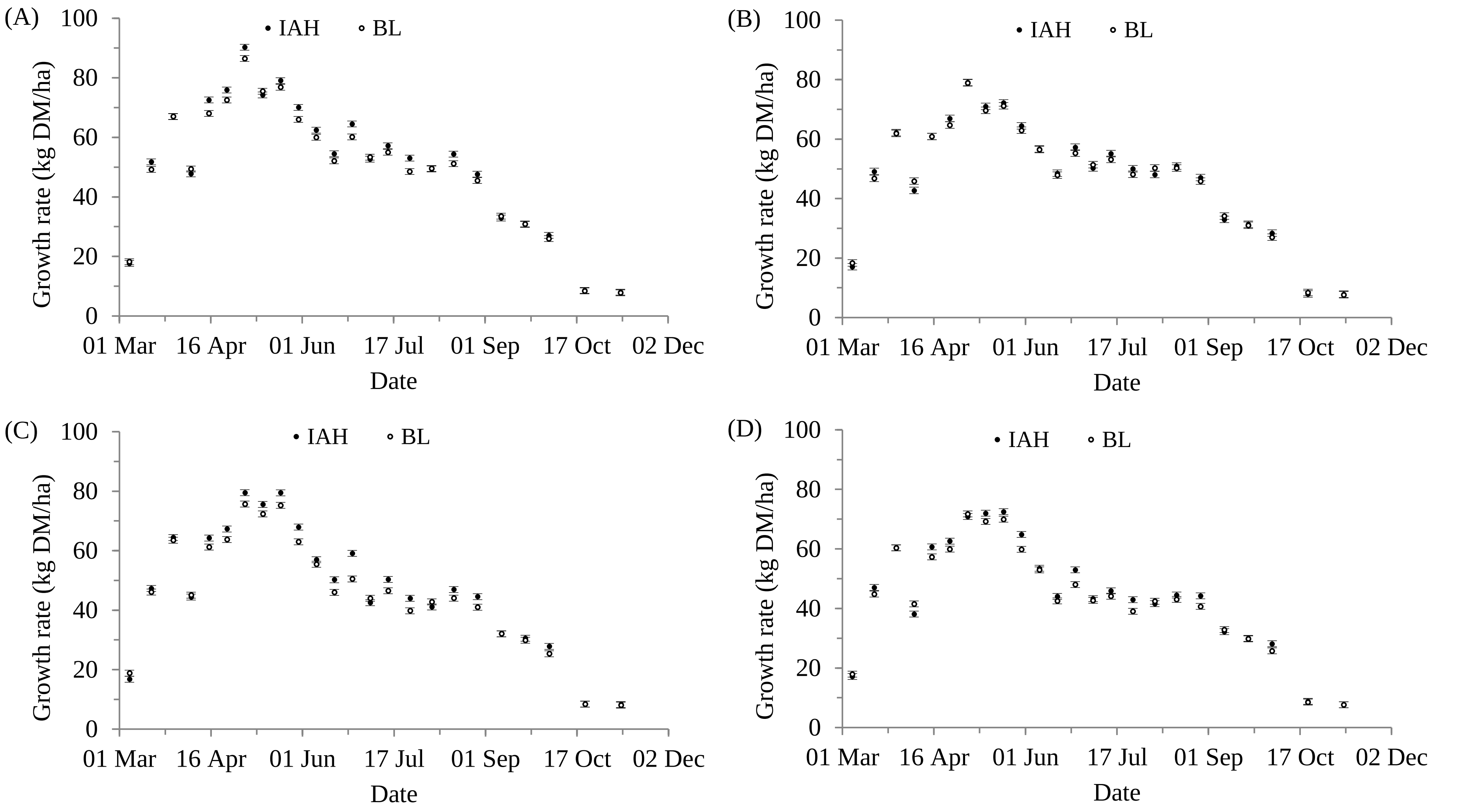
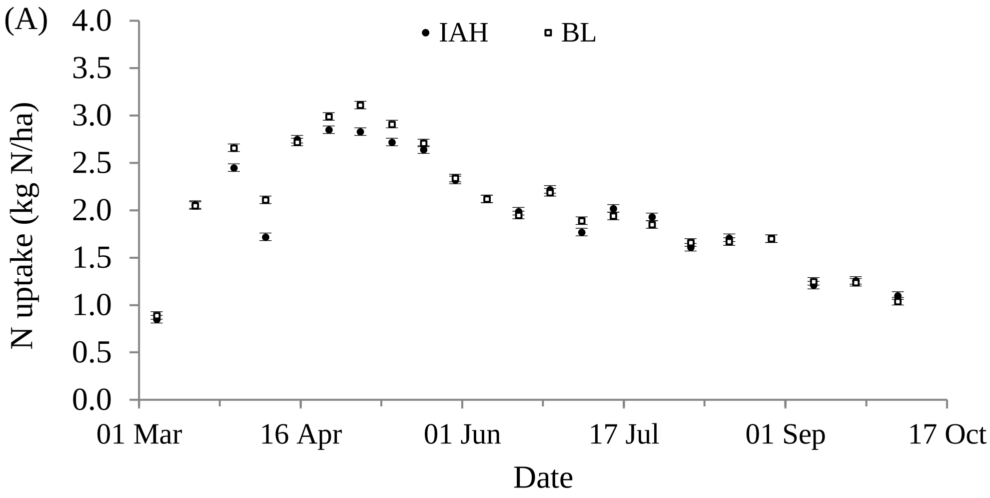


Figure 4.3 Daily growth rates (kg DM/ha) where fertilizer N was applied immediately after harvest (IAH) or using a Blanket approach (BL) for (A) CAN applied at a rate of 300 kg N/ha, (B) urea applied at a rate of 300 kg N/ha, (C) CAN applied at a rate of 200 kg N/ha and (D) urea applied at a rate of200 kg N/ha. Data are the mean of three replications, two sites and two years.



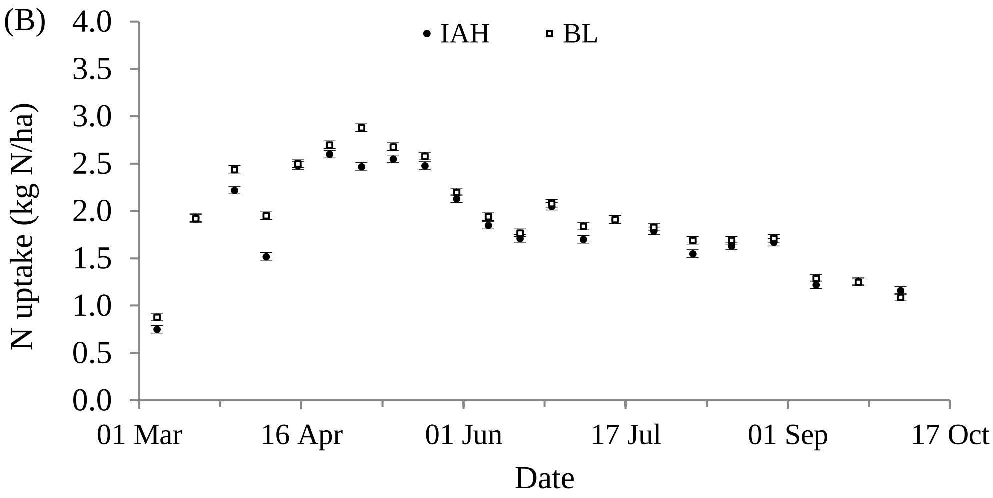


Figure 4.4 Daily N uptake (kg/ha) where fertilizer N was applied immediately after harvest (IAH) or using a Blanket (BL) approach for (A) CAN applied at a rate of 300 kg N/ha and (B) urea applied at a rate of 300 kg N/ha. Each data point is the mean of three replications, two sites and two years. I = ± SEM.

Table 4.5 Daily grass growth rates (kg DM/ha) where fertilizer N (CAN and UREA) was applied immediately after harvest (IAH) or using a Blanket approach (BL); data are the mean of two rates of application of fertilizer N, three replications, two sites and two years. The optimum combination of fertilizer type and application strategy at different times of the year and the optimum fertilizer type if only applying fertilizer N IAH or BL at different times of the year.

Application date	CAN IAH	CAN BL	UREA IAH	UREA BL	SEM	Optimum strategy	Optimum fertilizer if applied IAH	BL
31 Jan	17.2	18.5	17.1	18.1	0.42^NS	UREA BL	UREA	UREA
18 Feb	49.6	47.7	48.1	45.8	0.81*	UREA IAH	UREA	CAN
28 Feb	65.7	65.3	61.3	61.1	0.89***	CAN BL	CAN	CAN
07 Mar	46.1	47.2	40.4	43.7	0.95***	CAN BL	CAN	CAN
18 Mar	68.4	64.6	60.8	59.1	1.55***	CAN IAH	CAN	CAN
28 Mar	71.6	68.2	64.8	62.3	1.16***	CAN IAH	CAN	CAN
05 Apr	84.9	81.1	75.0	75.4	1.28***	CAN IAH	CAN	CAN
14 Apr	74.9	73.9	71.5	69.5	1.25*	CAN BL	CAN	CAN
24 Apr	79.3	76.0	72.4	70.6	0.86***	CAN IAH	CAN	CAN
03 May	69.0	64.5	64.6	61.4	0.98***	CAN IAH	CAN	CAN
12 May	59.7	57.7	55.1	54.7	0.75***	CAN IAH	CAN	CAN
21 May	52.3	49.0	46.3	45.2	0.72***	CAN IAH	CAN	CAN
30 May	61.8	55.3	55.1	51.6	0.94***	CAN IAH	CAN	CAN
08 Jun	47.6	48.7	46.8	47.1	0.68^NS	CAN BL	UREA	CAN
17 Jun	53.8	50.7	50.5	48.6	0.59***	CAN IAH	CAN	CAN
27 Jun	48.5	44.2	46.5	43.6	0.54***	CAN IAH	CAN	UREA
06 Jul	45.2	46.2	44.9	46.4	0.62^NS	UREA BL	UREA	UREA
17 Jul	50.7	47.6	47.7	46.7	0.35***	CAN IAH	CAN	UREA
04 Aug	46.1	43.3	45.7	43.3	0.63**	UREA IAH	UREA	UREA
15 Aug	32.5	32.8	32.6	33.5	0.33^NS	UREA BL	UREA	UREA
25 Aug	30.6	30.4	30.7	30.4	0.32^NS	UREA BL	UREA	UREA
29 Aug	27.5	25.7	28.3	26.4	0.37***	UREA IAH	UREA	UREA
09 Sep	8.5	8.4	8.4	8.5	0.11^NS	UREA BL	UREA	UREA
19 Sep	8.0	8.0	7.7	8.1	0.08^NS	UREA BL	UREA	UREA

4.5 Discussion

4.5.1 The weather and grass growth

The magnitude of differences in annual-average grass growth between SOR treatments was much greater in 2004 than 2005 (Table 4.3). Differences in grass growth and responsiveness to fertilizer N between years can be partially explained by differences in weather conditions between the two years. At Solohead during the summer (June, July and August) 2005 rainfall amounted to 138 mm compared with 255 mm during the same period at Solohead in 2004 and compared with 307 mm and 197 mm at Moorepark in 2004 and 2005, respectively. Lower rainfall during this period of high evapotranspiration explains lower grass growth at both sites in 2005 compared with 2004 and the greater depression in grass growth at Solohead in 2005 particularly during the summer months (Figure 4.1). Other aspects of weather conditions probably also contributed, such as the colder soil temperatures at Moorepark in May 2005, which is likely to negatively impact on grass growth. Drier conditions during the summer are also associated with greater N losses from urea than CAN (Chambers and Dampney, 2009; Forrestal *et al*. 2015). This is consistent with the lower grass growth in the treatments receiving urea compared with CAN in the present study.

4.5.2 Stages of regrowth

In terms of the amount of N applied at any one time regardless of SOR or fertilizer type, this study showed that grass DM yield increased with increasing N rate, thus indicating that within this range of N fertilization (200 to 300 kg N/ha), grassland in a maritime climate such as observed at both sites, as would be expected, responded to additional fertilizer N input (Hopkins *et al*. 1990; Forrestal *et al*. 2017).While grass growth rates were higher, in general, with IAH than the other SOR treatments, which is in agreement with McKee *et al*. (1967) and Brockman (1974), it is remarkable that there were no differences in average-annual grass growth rates between the different SOR where urea-N was applied at an annual rate of 300 kg/ha in contrast to the other fertilizer N input treatments. Furthermore, in contrast to 2004, there were no differences in grass growth between the SOR treatments at the higher rate of fertilizer N input in 2005. At the lower rate of fertilizer N the differences in annual average grass growth between SOR were less pronounced in 2005 than 2004. It seems that IAH gave the best response in terms of grass growth when conditions were better for grass growth in 2004 except for the higher rate of urea. The relatively poorer response to the higher rate of urea applied IAH can be explained by its application during the late spring and summer months under conditions that were not ideal for the best utilization of the urea N and the higher rate which can lead to inefficient use of N (Harty *et al*. 2017). This latter reason explains why there was a better response to the lower rate of urea applied IAH than the other two SOR treatments. Less efficient utilization of fertilizer N is also evidenced by higher concentrations of N in herbage DM particularly in the EM and ML SOR treatments. Therefore, the evidence (lower grass yields and higher N concentrations in harvested grass DM) contrary to the suggestions by Pain *et al*. (1998) suggests applying urea to a canopy of grass does not improve N-use efficiency by the sward. This has implications for losses of N to the environment. The higher N concentrations in grass DM with the EM and Ml treatments can be attributed to luxury uptake and insufficient time for the N to be fully utilized by the grass between uptake and harvest. Furthermore, if this grass were to be consumed by grazing dairy cows, these higher concentrations of N would be more-or-less entirely excreted in urine and thus the N is inefficiently recycled back to the soil (Van der Meer and Van Uum-Van Lohuyzen 1986; Delaby *et al*. 1997).

4.5.3 Fertilizer N application strategies and effective production

The differences in annual average grass growth between IAH and BL reflect the differences in SOR outlined above in terms of differences between rates of application, fertilizer types, sites and years. The time of year when the fertilizer N was applied influenced the difference in grass growth response between the strategies at different times of the year (Table 4.5). There are also other considerations such as (i) the price differential between urea and CAN, (ii) labour and cost savings associated with BL (Ferris *et al*. 2008) and (iii) the limits on the amount of fertilizer N that can be applied to grassland under the Nitrates Directive regulations in Ireland (SI 31 2014). Therefore, with the latter constraint, it is necessary to maximise grass production response per kilogram of applied fertilizer N because additional grass grown as a consequence of the application of fertilizer N is much cheaper than alternative feeds (Hanrahan *et al*. 2018). Where there is no delectable difference in herbage production response between application strategies, the cost-effectiveness of strategies can be ranked: UREA BL < UREA IAH < CAN BL < CAN IAH (as outlined above). Hence, it is possible to determine the optimum combination of fertilizer type and fertilizer application strategy at different times of the year (Table 4.5). In general, a BL approach is a more cost-effective approach early in the growing season, between mid-January and mid-March, and in the latter part of the growing season, between mid to late July and the end of the season. Using BL at these times of the year also ties in with typical grazing management with long inter-grazing intervals (rotations) during the spring and during the late summer and autumn. In the spring on Irish dairy farms, if soil conditions allow, cows are typically turned out to grass in early to mid-February and the first grazing rotation is completed in early to mid-April, which is an interval of 60 days or so. With the first application of fertilizer N applied between mid-January and mid-February and the second application between mid-February and mid-March, a BL approach is unlikely to have any negative impact of grass growth compared with IAH. With the completion of the first grazing rotation in early to mid-April an IAH approach should be followed to ensure best responsiveness to applied fertilizer N. Rotation lengths from mid-April typically range between 18 and 24 days until around mid-July after which rotation lengths are allowed to increase to up to 42 days in order to build up a bank of grass during the late summer and early autumn to extend the grazing season into the late autumn and early winter. Hence, a BL approach also ties in well with longer rotations in the latter part of the growing season.

Contrary to current recommendations urea was only as cost effective as CAN for applications between mid-January and mid-February. This is in agreement with some studies which reported CAN applications resulting in higher DM yield with urea only obtaining anywhere between 85-95% of CAN in spring (Van-Burg *et al*. 1982; Watson and Adams, 1986; Antille *et al*. 2015). However, other studies (Herlihy, 1988; Stevens *et al*. 1989; Forrestal *et al*. 2017) showed that urea could equal or indeed outperform, although not significantly (103%), CAN in terms of grass DM production over the spring period. In our study the use of CAN remained the most cost effective approach until early to mid-July. From then onwards urea was as cost effective as CAN which is in agreement with current recommendations and Keane *et al*. (1974) and Forrestal *et al*. (2017). Both these studies were conducted over two growing seasons as was Keane *et al.* (1974). In that study there was inconsistency in the DM yield performance of fertilizer type at first harvest in spring between years. In the first year DM production as a result of using urea was similar to this study being less (95%) than that of CAN in spring and in the second year it was similar to Forrestal *et al.* (2017) at 103% that of CAN in spring. Furthermore, summer DM yield as a result of using urea was found to be 103-104% that of CAN, which contradicts the two more recent studies which indicated urea performance to be either similar to or 98% of CAN during the summer. The contradiction in results and the seasonal variation in the DM performance of fertilizer type as observed in these studies, highlights the influence of interacting factors such as N application timing, rate, soil type and the significant impact meteorological conditions and the variation of these conditions have from one year to another on grass growth. If so, studies with too short a time frame, may actually be biasing findings. Therefore, longer term studies would be better for reaching more reliable and balanced conclusions. For instance, Long and Gracey (1990) reported that the form of fertilizer N had no significant effect (P>0.05) on first harvest in May and total annual grass DM yields, nor on N uptake by herbage at the first harvest in six experimental years. However, the performance of urea and of CAN was more variable at the second harvest in July and the third harvest in September.

4.5.4 Choice of fertilizer N application strategy

Our study has shown that IAH application of fertilizer N results in the highest levels of grass DM production when using CAN but not for urea at higher rates of N fertilization. The ultimate purpose of grass DM is for milk production in dairy systems (Ribeiro Filho *et al*. 2005). A study in Northern Ireland (Ferris *et al*. 2008) observed no difference in milk yield or milk constituents whilst comparing two systems of production, one involving fertilizer N application within a few days post grazing ("frequent/IAH") and the other with only one application occasion ("infrequent/BL") within a grazing cycle. This may indicate that any small drop in grass DM production as seen in our study, as a result of reduced spreading frequency can actually be compensated for by better grass DM utilisation and thus no negative impact on animal performance in the grazing system. If no negative impact on milk production is the case, then the cost and ease of producing each t of grass DM comes sharply into focus.

Treacy (2008) recorded the number of fertilizer application events on intensively managed dairy farms from 2003 to 2006. Results indicated that IAH N application was not in the truest sense happening at farm level. The majority of farmers in that study were neither following an IAH nor a BL strategy. The reality lay somewhere in between these two extremes with a group average of around one application per week (Humphreys *et al*. 2006). Therefore in most cases in order to reach the higher levels of DM production farmers would instead have to increase the amount of time spent applying fertilizer N rather than reducing it. This is highly unlikely to happen as in the last decade labour availability has become even more of a constraint on Irish dairy farms (O'Donovan, 2008; Dillon *et al*. 2017).

This situation has been created by increased demands on farmer's time arising from larger animal numbers, farm expansion since the removal of milk quota in 2015 and the lack in availability of additional farm labour (Dillon *et al*. 2018). The observed rise in the use of BL application strategies on farms in recent years suggests that farmers have identified BL application of N as an opportunity to use off farm labour in order to better manage workloads on farms (Dillon *et al*. 2018). Ferris *et al*. (2008) had a strong focus on labour use and showed the labour-saving benefits of BL application. The study indicated that even though there was only a small difference (24.1 min/wk) in time saving between infrequent (BL) and frequent (IAH) N application strategies the time spent in an infrequent system is combined into one occasion allowing for a contractor to be used. This may prove to be the key determining factor in choosing how fertilizer N is to be applied in a scenario where the availability of on-farm labour is continually scarce (People in dairy project report, 2017). If farmers remain constrained to using a BL approach throughout the growing season the optimum fertilizer type to use at different times of the year is outlined in (Table 4.5). Likewise, for farmers only using an IAH approach (Table 4.5).

4.6 Conclusion

In general the combination of CAN fertilizer applied IAH gave highest grass production and most efficient utilization of fertilizer N. However, there were instances during the growing season when alternative strategies to CAN applied IAH could equal the productivity and be more cost-effective. Early in the growing season (mid-January to mid-February) the BL application of urea was the most cost effective approach; likewise in the late summer and autumn from mid-to late July onwards. CAN applied BL was most cost effective for the second application between mid-February and mid-March. Hence a BL approach to fertilizer N application can be integrated into an annual fertilizer N application strategy between January and mid-March and from July onwards with little or no loss of production provided that fertilizer N is applied IAH at other times of the year. Such an approach can be easily integrated into typical grazing management with long inter-grazing intervals during the spring and during the late summer and autumn.

Chapter 5 General discussion and conclusions

A major challenge facing Irish dairy farmers today is the demanding workload they face on a daily basis. This workload has increased in recent years as farmers have expanded their enterprises after the phasing out of the milk quota. In many instances this expansion has not been matched by a proportional increase in labour availability. This is partly due to financial constraints and mostly to lack of available skilled labour.

Another challenge relates to the use of mineral fertilizer N on farms as it has become much more tightly regulated over the past two decades. This is due to the harmful effects inappropriate use can have on the surrounding environment. The cost of mineral fertilizer N as an input has also increased significantly during the same period. Consequently farmers are motivated to be mindful of nitrogen fertilizer type, timing and rate of fertilizer application.

When the aforementioned factors are taken into consideration in their entirety, it is not surprising that the use of a blanket fertilizer N application strategy has become more prevalent on Irish dairy farms. Farmers have identified this approach as a means to cope with limited on-farm labour availability by using contractors to blanket apply fertilizer. Also the smaller number of application events means that it is easier to apply the most suitable type of fertilizer N at different times throughout the year and be more accurate in the amount of fertilizer N that is applied. Therefore application on farms can be done in a controlled and well-planned manner that will optimise agricultural productivity and minimise environmental damage.

A planned approach aimed at getting the best DM response to fertilizer N application begins with the first round: Urea can be applied between mid-January and mid-February at a rate no more than 30 kg N/ha across all paddocks. This needs to be followed five weeks later (between mid-February and mid-March depending on when the initial first application took place) by a second application of CAN using a blanket approach at the same rate or greater (up to 60 kg N/ha) depending on stocking rate (Table 4.1).

Between early April and mid-July CAN should be applied to each paddock immediately after grazing in order to ensure the best DM response to applied fertilizer N. This period should encompass the third, fourth, fifth and sixth rounds of fertilizer N application (Table 4.1).

From the beginning of August until the deadline for fertilizer application in mid-September, there are typically two applications of N on intensively stocked farms. In both instances the optimum approach is to blanket apply urea.

The overall fertilizer N spreading programme as outlined above highlights three key aspects, (i) that initial fertilizer N applications in spring should involve two smaller applications spread apart from each other rather than one large one, (ii) that there is an appropriate fertilizer type to use at different times of the year and finally (iii) that fertilizer N can be applied using a blanket approach in the first two rounds in spring and the last two rounds in autumn without any negative impact on productivity.

This work was carried out between 2004 and 2006 and used the two most common forms of straight N being utilised on Irish dairy farms at that time. CAN and urea still remain as popular as ever but in more recent years other straight fertilizer N types have come onto the market, particularly protected urea, which has been shown to reduce nitrous oxide and ammonia losses compared with CAN and urea, respectively (Harty *et al*. 2016; Forrestal *et al*. 2017). As agriculture must meet future commitments to reduce GHG and ammonia emissions, the use of protected urea and other new formulations will inevitably become more widespread. Nevertheless, although it needs further investigation, it is likely that applying protected urea immediately after grazing can potentially give a more efficient grass DM production response and will also reduce N loss to the environment as opposed to blanket application between April and July. Blanket applications should be used at other permissible times of the year.

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