Eutrophication from Agriculture Sources
2000-LS-2-M2

FINAL REPORT (SECTION 3 OF 3)

Nitrate Leaching - Farm Scale
(2000- L S 2.3.1.1-M2)

NCYCLE_IRL - A model to predict N fluxes in Irish grasslands

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DISCLAIMER

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Final Report Section 3 of 3

NCYCLE_IRL - A model to predict N fluxes in Irish grasslands

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CONTENTS Page

Acknowledgements………………………………………………………………….. ii

Table of Contents ………………………………………………………………iii

Summary………………………………………………………………….…...iv

Keywords……………………………………………………………..……..v

1. Introduction…………………………………………………………...1

2. Stages to the develop NCYCLE_IRL……………………………………..2

2.1 Development of grassland agroclimatic areas for Ireland…………………….2
  2.1.a Comparison of weather patterns in Ireland and in the UK…………....2
  2.1.b Studies on variability of grass production across Ireland……………...7
  2.1.c The approach to develop the agroclimatic areas……………………….7
2.2 Development of a new mineralisation submodel……………………….....8
2.3 Mapping atmospheric N inputs….……………………..……………...10
2.4 Simulation of plant N uptake………………………………………….10
2.5 An evaluation of the need to include urea as a fertiliser N type in NCYCLE_IRL………………………………………………...11
  2.5.a Fertiliser N use – type ……………………………………….....11
  2.5.b Main N flow pathways following urea applications to soil……..……..11
  2.5.c Impact of urea fertilisation on herbage production in Ireland………….15
  2.5.d Conclusion of evaluation......……………………………...………...16
2.6 Updating with new functios for animal production and excreta N division and producing a new NH_3 generator submodel………..……….....17
  2.6.a Animal production and excreta N division……………………….…17
  2.6.b Refining the NH_3 generator sub-model………………………..…..20
2.7 Producing a new denitrification and leaching submodel……………….……22
2.8 Coding the main model and interface in DELPHI 5…………………….…...23
2.9 Validation of NCYCLE_IRL…………………………………….…..28
  2.9.a Herbage………………………………………………………...28
  2.9.b Denitrification………………………………………………….…32
  2.9.c Leaching……………………………………………………..32
  2.9.d Effect of soil type on N losses…………………………………….…32

3. NCYCLE_IRL as a tool to analyse N leaching in Ireland……………….……...33

3.1 Dairy grazed grasslands……………………………………….…….33
3.2 Grasslands for silage production……………………………………….34
3.3 Practicality of the NCYCLE_IRL approach……………………………34

4. Conclusions………………………………………………………….....35

5. References………………………………………………………….…37

SUMMARY

The sources, pathways and impacts of diffuse nutrient losses from agriculture, including nitrate (NO_3) leaching, that contribute to eutrophication of water-bodies have been studied internationally for at least three decades. The European Union has introduced legislative controls to address them (EC, 2000 and EEC, 1991). Water quality in Ireland is generally good compared with many other European countries. However, eutrophication remains probably Ireland's most serious environmental pollution problem (EPA, 2002). While progress is being made in addressing the issues, there remains a significant challenge in achieving the required balance between sustainable production and environmental protection not least because grassland agriculture takes place in an open environment with variable soils and weather that are generally outside the control of the farmer.

In address this challenge, there is a need to develop tools that can link production with N losses to the environment. The Institute of Grassland and Environmental Research was contracted to undertake this study which was to develop its NYCLE empirical modelling approach (Scholefield et al., 1991) that would predict N fluxes from Irish grassland systems and provide outputs of leached, denitrified, volatilised, mineralised and milk N at farm scale.

The steps required to develop NCYCLE_IRL involved a review of the literature and ongoing experiments on N cycling in Irish agroecosystems, the update and creation of new sub-model routines, the creation of a new interface with an object- oriented programming language (DELPHI 5) and the validation of some of the N pathways with Irish data. The following were key outputs:

1. The literature on N fluxes and weather patterns suggested that the differences between Ireland and the UK are largely based on the generally longer grass growing season in Ireland. Regional grass growth patterns were studied and six Irish agroclimatic zones for grass were identified and modelled into NCYCLE_IRL.

2. Experimental data relating soil type and drainage class to N fluxes was used to build these differences into NCYCLE_IRL.

3. Urea accounts for 17% of N fertiliser use in Ireland. Urea was not included as a fertiliser N type input in NCYCLE_IRL. This decision was based on a literature review which showed that the likely negative impact of its use compared with other fertiliser N types (CAN or AN) on production or leaching losses were likely to be confined to summer and early autumn applications.

4. New functions were developed to improve the animal and NH_3 volatilisation sub-models to predict more accurately flows of N in milk, meat, excretion and NH_3.

5. The average NO_3-N concentrations in the leachate immediately below the rooting zone is derived in NCYCLE_IRL from the division of the leachable N load by the effective rainfall. Peak NO_3-N concentrations in groundwater and

NO_3-N in the first 25 mm of drainage water are calculated using the relationships in the original NCYCLE.

NCYCLE_IRL represents one of the first attempts to integrate the available data on N cycling in Irish grasslands. Modifications to some of the existing functions in the original NCYCLE (animal capture in the rumen, partition of excreta, NH_3 volatilisation) and values for existing parameters (N from atmosphere, N from mineralisation from previous years) improved the predictions from the original version. The applicability of NCYCLE_IRL was also enhanced by incorporating the peak and average N concentration in the leachate, which allows the evaluation of the implications of environmental control measures. The model also succeeded in incorporating the existing Irish agroclimatic and atmospheric N deposition studies into a simple and integrated approach. The predictions of N losses and yields for Irish conditions agreed well with the expected and measured ranges. Further development of the applicability of the model will require more integrated N studies, the scaling up to farm level and the introduction of a shorter time-step, possibly monthly.

Keywords

Nitrate leaching, nitrogen fluxes, grassland management, volatilisation, modelling, dairy farming.

1. INTRODUCTION

Agriculture is an important contributor to Ireland's economic activity accounting for a 1.8% share of Gross Domestic Product in 2005. Agricultural production is primarily grass-based animal production enterprises that account for almost 80 % of gross agricultural outputs. Grassland productivity is responsive to nitrogen (N) fertiliser and as agricultural output increased over the last 50 years so have N inputs. The most recent fertiliser survey (Coulter *et al.,* 2002) showed that average annual N use on grasslands was 136 kg N ha^{-1} (48 and 176 kg N ha^{-1} for the beef and dairy-grazed grassland, respectively, and 95 and 151 kg N ha^{-1} for the beef and dairy grassland for silage, respectively).

Beef and dairy production systems in Ireland are and will continue to be based on grazed grass during the grazing season and conserved grass during the winter. About 82 % of all farms make silage, producing a total of 4.4 million tonnes silage dry matter (DM) per year (O'Kiely *et al.,* 1998). Cows normally calve in February so that lactation coincides with the period of active grass growth. About 90 % of the annual feed is home-produced from grass (Fitzgerald *et al.,* 2003).

Connolly *et al., (*2002) indicated that average stocking rates on dairy farms in Ireland are a little less than 2 livestock (LU) ha^{-1}. Irish dairy production is characterised by relatively low milk production per cow and low costs of production compared with other European countries. However, as in many other EU countries, agricultural land is regarded as the main source of nitrate (NO_3) in Irish rivers and groundwaters (EPA, 2002). Although the EPA (2002) concluded that water quality in Ireland was generally good compared with many European countries, it identified eutrophication of inland fresh waters as "probably Ireland's most serious environmental pollution problem".

The identification of increasing levels of NO_3 and eutrophication in Irish water bodies and the implementation of national legislation to give effect to European water quality directives (EC, 2000 and EEC, 1991) requires methods of predicting NO_3^- leaching responses to mitigation strategies. The NCYCLE (Scholefield *et al.,* 1991) modelling approach offers such potential.

NCYCLE is a mass balance empirical model that has been developed in the UK for grassland and calculates the annual N transformations, fluxes and losses for cut and grazed grassland at the field scale, based on inputs specifying climatic zone, soil texture and drainage class, sward management, age and fertiliser input. The annual leachable NO_3 load is predicted on a per hectare basis. The model also enables the overall efficiency of N use to be calculated, so that the feasible trade-offs between production and environmental impact can be identified. Gaseous N losses as ammonia (NH_3) and nitrous oxide (N_2O) and di-nitrogen (N_2) from denitrification are also calculated.

NCYCLE was developed to improve its applicability to Irish conditions. The new model, NCYCLE_IRL provides a means by which NO_3^- leaching, peak and average concentrations in drainage water may be predicted for different soil, climate and management scenarios.

2. REFORMULATION OF NCYCLE INTO NCYCLE_IRL

The NCYCLE model was developed at the Institute of Grassland and Environmental Research (IGER), North Wyke, Devon, UK, using the results of measurements made on 10 long term field grazing systems (Scholefield *et al.,* 1991). NCYCLE is an empirical, deterministic and mass balance model which calculates average annual fluxes of N per hectare within a beef or dairy grazing system and cutting only system. The input parameters are: soil texture, drainage status, land use history, age of sward, climatic zone and atmospheric deposition zone. The model is user friendly and does not require a detailed knowledge of computing. The key sub-model in NCYCLE uses linear regression to partition the annual flux of soil inorganic N between 'plant N' and the surplus of mineral N in the system which is available for gaseous and leaching losses. Sward age and management, climatic zone and soil characteristics exert an important influence on the amount of N mineralised within a year. The proportion of plant N that is ingested by the animal can then be adjusted according to grazing pressure. Ingested N is then partitioned between product N (meat or milk) and excreted N (urine and dung), which is returned to the N pools in the soil. Inorganic N can be then lost via volatilisation (from urine and dung), denitrification and leaching. Nitrogen lost by denitrification is calculated using a sub model based on soil texture and drainage status. The surplus N that is neither volatilised nor denitrified is accumulated in the leachable N pool.

The development of NCYCLE_IRL required the reformulated of NCYCLE. The original NCYCLE was coded in PASCAL. NCYCLE_IRL was coded in DELPHI 5, an object-oriented, Pascal-based programming language. The steps in the reformulation process were:

2.1 Development of grassland agro-climatic areas for Ireland.
2.2 Development of a new mineralisation submodel.
2.3 Production of a new map of inputs of N from the atmosphere.
2.4 Simulation of plant N uptake.
2.5 An evaluation of the need to include urea as a fertiliser N type in NCYCLE_IRL.
2.6 Producing a new NH_3 generator submodel and updating the functions for animal production and excreta division.
2.7 Producing the new denitrification and leaching submodel.
2.8 Coding the main model and interface in DELPHI 5.
2.9 Validation using field data.

2.1. Development of grassland agro-climatic areas for Ireland

This step was divided into three subsections:

2.1.a. Comparison of weather patterns between Ireland and the UK.
2.1.b. The regional variability of Irish grass production.
2.1.c. Developing the agro-climatic areas for NCYCLE_IRL.

2.1.a Comparison of weather patterns between Ireland and the UK

Climatic variables from 30 year-datasets were used to compare Irish weather patterns with corresponding ones in the UK. Monthly average temperature and rainfall at six stations in Ireland were graphed and compared with corresponding data from six climatic regions in the UK. The results indicate that the temperature and rainfall values in Ireland were within the range of UK values (Figures 2.1 to 2.12). There was good agreement between the rainfall data for both countries. However, some Irish locations had higher winter temperatures (e.g. Figure 2.5). This analysis suggests that for most Irish locations, the weather conditions will be similar to those for some UK regions but some small differences should be expected in the N processes that are highly dependent on temperature (mineralisation, plant uptake, denitrification and indirectly, leaching). In addition, the growing and probably the grazing season would tend to be slightly longer in Ireland compared with the UK.

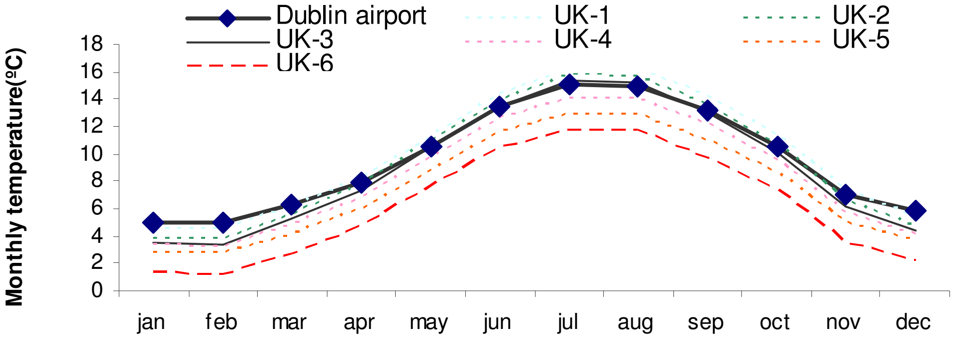


Figure 2.1. Comparison of Dublin airport temperature with temperature from six UK climatic regions

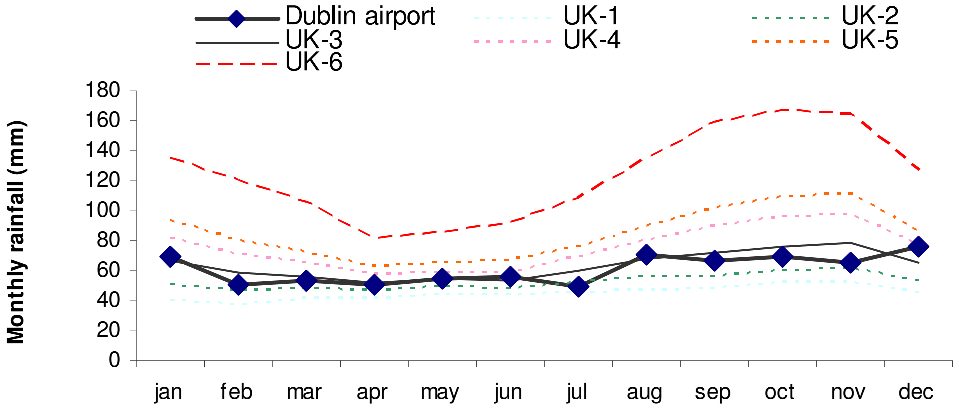


Figure 2.2. Comparison of Dublin airport rainfall with rainfall from six UK climatic regions

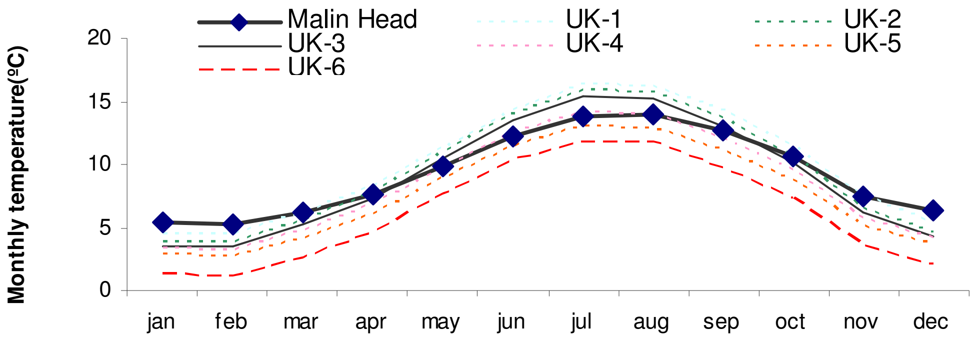


Figure 2.3. Comparison of Malin Head temperature with temperature from six UK climatic regions

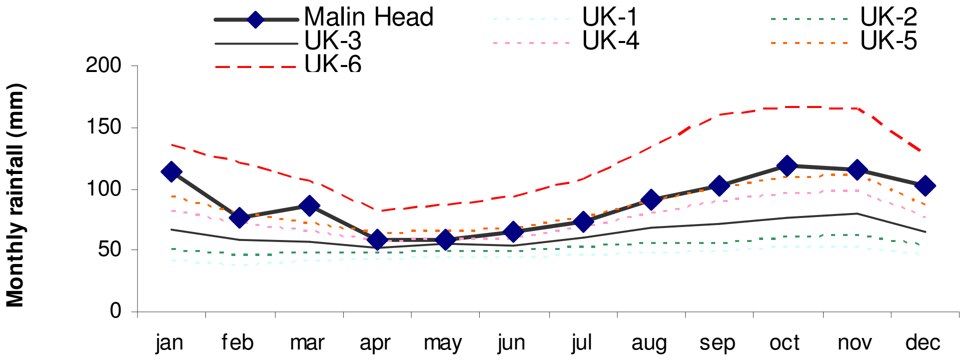


Figure 2.4. Comparison of Malin Head rainfall with rainfall from 6 UK climatic regions

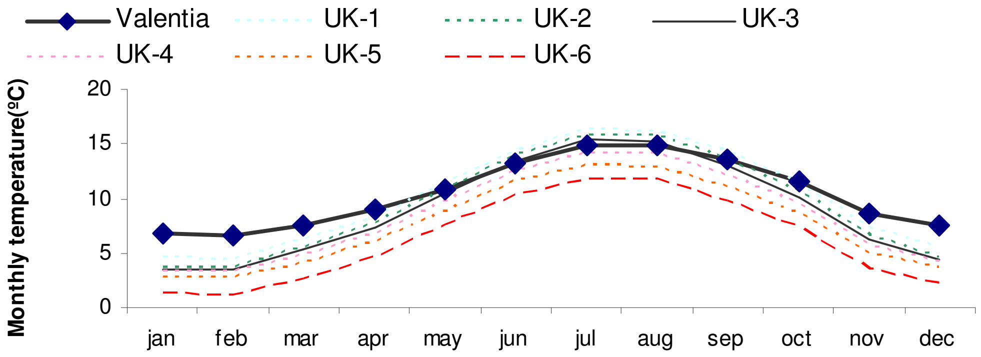


Figure 2.5. Comparison of Valentia temperature with temperature from six UK climatic regions

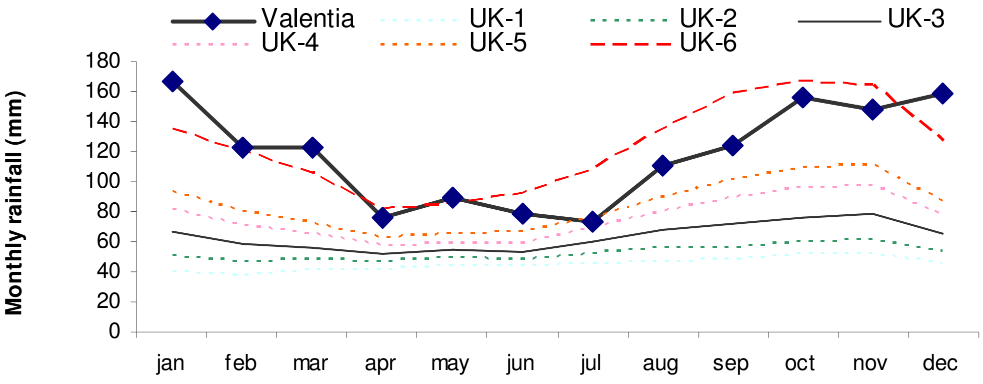


Figure 2.6. Comparison of Valentia rainfall with rainfall from six UK climatic regions

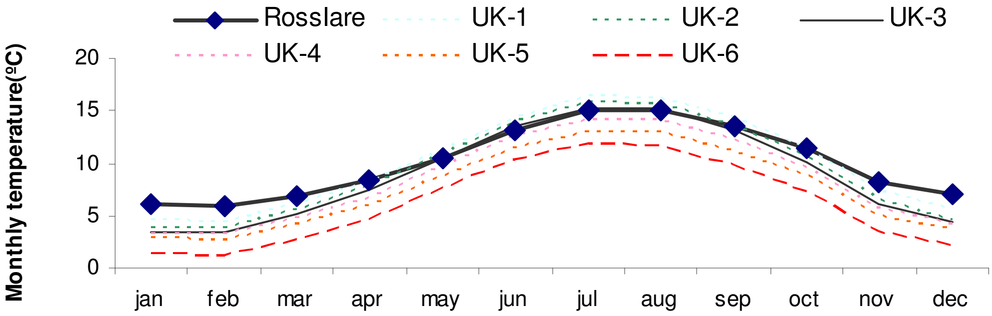


Figure 2.7. Comparison of Rosslare temperature with temperature from six UK climatic
regions

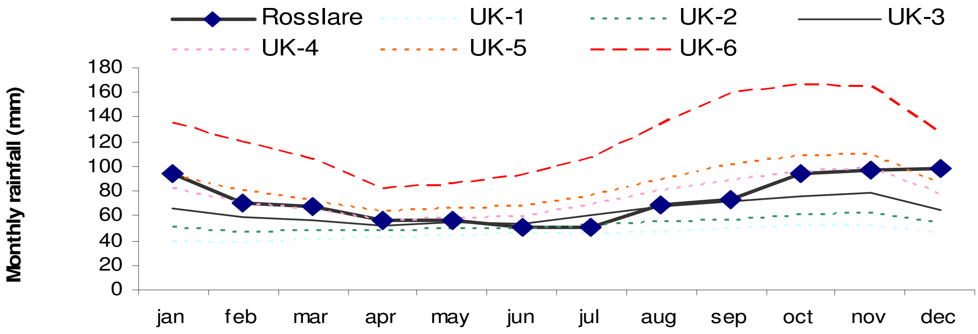


Figure 2.8. Comparison of Rosslare rainfall with rainfall from six UK climatic regions

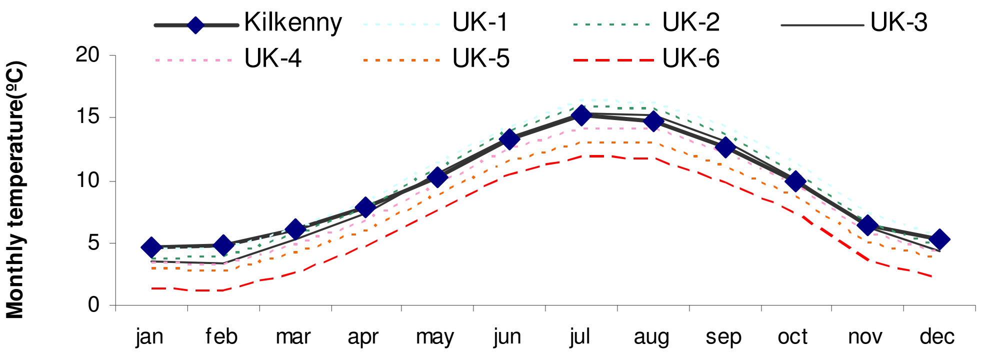


Figure 2.9. Comparison of Kilkenny temperature with temperature from six UK climatic regions

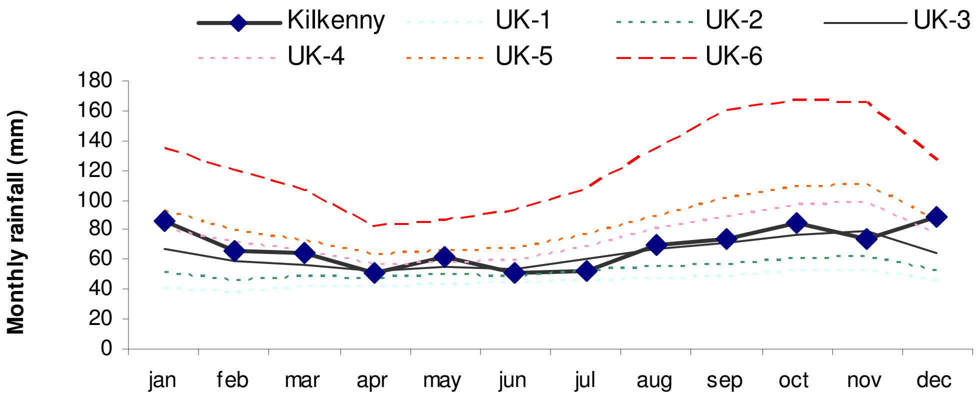


Figure 2.10. Comparison of Kilkenny rainfall with rainfall from six UK climatic regions

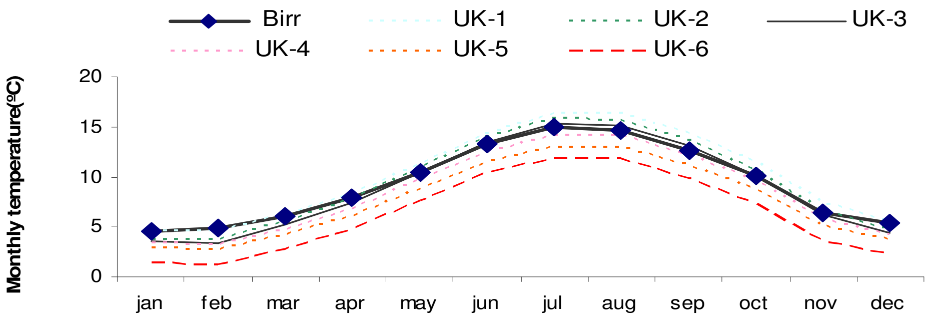


Figure 2.11. Comparison of Birr temperature with temperature from six UK climatic regions

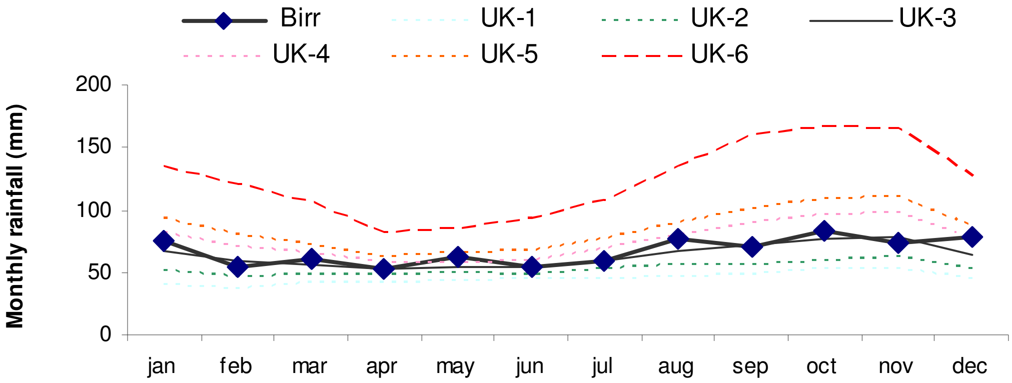


Figure 2.12. Comparison of Birr rainfall with rainfall from six UK climatic regions

2.1.b The regional variability of Irish grass production.

The regional variability of Irish grass production has not been studied in detail, possibly because the variations are small compared with those for mainland Europe (Brereton, 1995). However, published results on measured grassland productivity at 26 sites, covering a range of soil types and drainage classes, indicated regional production differences for similar soil types (Ryan, 1974 [a,b] and Ryan, 1976).

Some studies used the growing degree-days approach to illustrate regional differences (Burke, 1968; McEntee, 1978), while others, (e.g. Brereton, 1995) used weather-driven grass growth models that consider the regional variations in the parameters (radiation, temperature and rainfall). The most recent example by Holden and Brereton (2004) used hydro-thermal climate with a statistical clustering technique to relate grass yield to climate variability using crop simulation models. This study indicated the existence of different general agro-climatic areas and some qualitative references are made with respect to grass.

2.1.c Developing the agroclimatic areas for NCYCLE_IRL

In order to evaluate and quantify the differences in grass production between Irish grassland climatic zones, should they exist, site specific herbage N and DM yields from trials of Ryan (1974a, b, 1976) were allocated to the agroclimatic zones defined by Holden and Brereton (2004). This study indicated the existence of different general agroclimatic zones in Ireland and some qualitative references are made with respect to grass. The results of Ryan (1974a, b, 1976) obtained from the same soil types but in a different region were compared and factors were produced and tested against the approach of Holden and Brereton (2004).

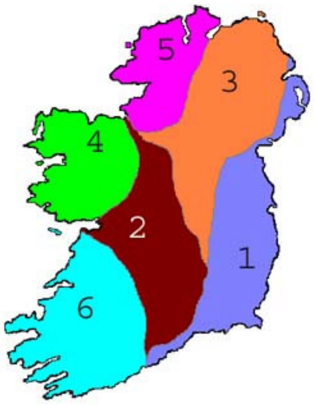
In NCYCLE, the main differences in herbage yields are caused by variations in the annual fluxes of soil available N. Therefore, the difference in N fluxes between the agroclimatic regions is a consequence of soil N mineralization rates. Annual soil mineralised N from the different soils and regions was derived from the zero-fertilised plots of Ryan (1974a, b, 1976). By assuming that the total harvested herbage N yield is 70 % of the total N in the plant, plant N uptake was obtained and related to the total annual N flux by using the following function derived from the original NCYCLE:

$$N_{\text{in dead plant}} + {}_{\text{mineralised}}N_{\text{from soil}} + {}_{\text{atmospheric}}N = 0.0007 *{}_{\text{plant}}N_{\text{uptake}}^{2} + 0.8135 *{}_{\text{plant}}N_{\text{uptake}} + 14.804 \qquad \textbf{(1)}$$

The grass yield from the N fixed by clover swards was estimated from the fraction of clover in the DM, assuming an N content in clover of 4 % (Thomas 2004), and subtracting this from the total herbage N yield. Nitrogen released to the soil from dead plant material was also accounted for using a NCYCLE function. This relates the N not removed from the total herbage N with the N concentration in the herbage.

Atmospheric N was estimated for different parts of Ireland by using the atmospheric map information of Jordan (1997). Estimates of the N mineralised from the soil can be obtained from equation 1.

There was reasonable agreement between the Ryan (1974 ^{a,b}, 1976) data and the yields measured in the agroclimatic zones when the effect of the soil type and drainage was removed. Ryan's data indicates the highest mineralisation rates occurred in the zone 6 (South and south-west Munster), followed by zones 2, 1, 4 and 3 (Figure 2.13). Ryan (1974 ^{a,b}, 1976) did not include sites for parts of Ulster. Therefore, assumptions were made for zone 5 in order to provide coverage for the country (Figure 2.13).



Zone 6 (factor 1.00)

Zone 2 (factor 0.87)

Zone 1 (factor 0.84)

Zone 4 (factor 0.77)

Zone 3 (factor 0.70)

Zone 5 (factor 0.60)

Figure 2.13. Agroclimatic regions in Ireland (after Holden and Brereton, 2004)

The mineralization adjustment factors for each zone are also shown in Figure 2.1.3. For instance, grassland in zone 4, with a similar soil and management history, has 77% of the N mineralised in zone 6. More detailed information on the mineralisation sub-model will be explained in section 2.2.

2.2 Development of a new mineralisation submodel

Mineralisation is considered to have two components in NCYCLE:

1. previous years' management.

2. current herbage yields and animal excreta.

Soil mineral N from previous years management is defined as the plant available N from the mineralisation of the previous years' N organic pools. In addition, there is an N supply from mineralisation of dead plant tissue and excreta under grazing management from the soil inorganic N component of the model.

The mineralisation rates for NCYCLE_IRL were developed from a multi-site cutting trial of long term grassland (eight to ten year-old) on a range of representative soil textures and a range of incremental fertiliser N inputs including zero N (Ryan, 1974[a,b], 1976). The rates were derived from the total herbage N yield (after subtraction of clover-N yield) of zero N plots multiplied by a factor (1.4) to allow for unharvested shoot and root material dying and mineralising during the season. The atmospheric deposition of N was also considered. It is assumed that the amount of dead plant tissue at the end of the season is equal to that at the beginning.

The analysis resulted in the identification of four soil types and five regions. As some of the regions did not have all soil types some extrapolations were required. The same factors used in the original NCYCLE (see Scholefield *et al*., 1991) were used to determine the mineralization rates for the four soil types and five regions. These factors included the history of the grassland (long-term grassland, mixed-ley arable and long-term arable), sward age (<2, 2-3, 4-6, 7-10, 11-20, >20 years), soil texture (sandy loam, loam, peat and clay loam) and drainage state of the soil (good, moderate and poor).

The soil N mineralisation adjustment factor, 2.5, for newly reseeded pasture (Table 2.1) reflects the increase in rates in the first year following reseeding (Young, 1986). Culleton and McGilloway (1995) and Culleton *et al.* (1989) reported a DM yield increase of about 40 % and 60 %, respectively, in the first year following the reseeding of long-term grassland. Other Irish studies (Brereton, 1995; Keating and O'Kiely, 2000), suggest lower yield increases of approximately 20 %, in the first year following reseeding. Approximately 2 % of the utilised agricultural land in Ireland is sown down to grass annually (N. Culleton *pers. comm.).*

The starting value for the mineralisation of soil organic N calculations depended on the history of the grassland (long term grassland: 280, mixed-ley arable: 105 and long-term arable: 42 kg N ha^{-1} yr^{-1}) and this value is subsequently modified by applying multiplicative adjustment factors to account for the age of the sward, agroclimatic zone, soil texture and drainage status (Scholefield et al. 1991). The multiplicative values are shown in Tables 2.1 and 2.2 and Figure 2.13.

Table 2.1. Adjustment factors applied to the amount of N mineralised from soil organic matter on the basis of previous cropping history of the field and age of existing sward

Previous Land	Age of sward (years)					
Use	1	2-3	4-6	7-10	11-20	>20
Long term grassland	2.5	1	1	1	1.25	1.5
Ley/Arable	2.5	2.25	2.25	2.5	3	3.5
Long-term arable	2.5	2.5	3	3.5	4	5

Table 2.2. Adjustment factors applied to the amount of N mineralised from soil organic matter on the basis of soil texture and drainage class

Drainage	**Soil Texture**			
	Sandy Loam	**Loam**	**Clay Loam**	**Peat**
Poor	0.38	0.72	0.50	0.50
Moderate	0.60	0.80	0.90	0.66
Good	0.75	1	1.15	1.03

2.3 Mapping atmospheric N inputs

NCYCLE_IRL uses information on rainfall chemistry presented by Jordan (1997). Two maps showing the regional variation in deposition of NO_3 -N and NH_4-N for the period 1992-1994 have been incorporated (Figures 2.14 a and b). Annual N deposition is generally below 5 kg ha^{-1} for NO_3-N over most of the country and is only exceeded in Wexford, part of south Wicklow and part of Donegal. Regarding annual NH_4-N deposition, for most of the island the annual mean N deposition is generally less than 6 kg ha^{-1} and is only exceeded in north east Antrim and in small areas of Wicklow and Dublin.

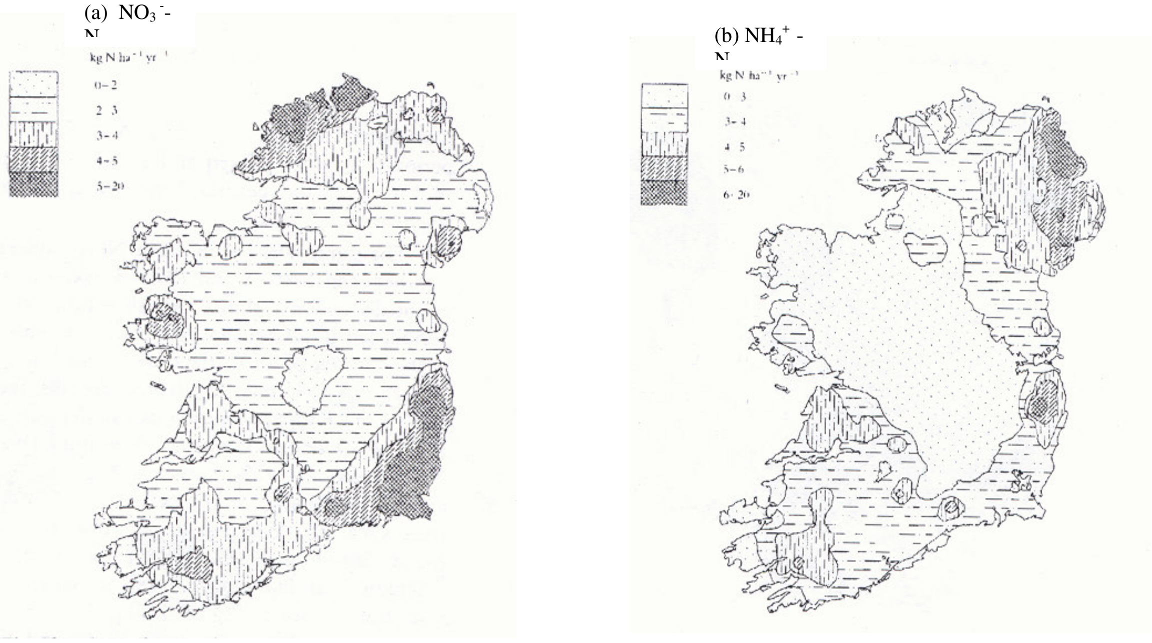


Figure 2.14. Maps of Ireland showing levels of atmospheric deposition of (a) NO_3 -N and (b) NH_4-N (after Jordan, 1997)

2.4 Simulation of plant N uptake

The N uptake by the plant competes with N loss processes from the soil mineral N pool using an approach similar to NCYCLE. The proportion of plant N uptake from the total inorganic N flux in the soil is calculated as a function of the total soil N flux. This relationship was found to be linear and negative, resulting in a higher proportion of mineral N flux being lost with increasing amounts of soil mineral N.

A proportion of the total plant N does not reach the animal, nor the silage, but decays in the soil, adding to the soil organic N pool that is subject to mineralisation. The difference between plant N and this dead tissue is herbage N. Different estimates of the N recovered by herbage have been reported, for example, 45 % by Ourry *et al.,* (1988) and 77 % by Hansson and Petersson, (1989). In NCYCLE, 62 % was proposed as the default value based on (Ball and Field, 1987). However, for NCYCLE_IRL the default value is 70% based on the results of Ryan, (1974[a,b]) and Ryan, (1976). However, the model allows the value to be changed by the user. This facilitates the investigation of the effect of changing this proportion (e.g., by changing grazing pressure) on N fluxes.

The proportion of dead plant mineralised during the grazing season is regarded by the model as being related to the herbage N concentration. It is assumed, that the mean N concentration of leaf litter and dead roots undergoing decomposition is 45 % of that in the herbage. The proportion of the dead plant that is then mineralised is obtained from the mean concentration of N in that fraction, as proposed by Jenkinson (1982). More details are available in Scholefield *et al.,* (1991).

A number of Irish studies were conducted to investigate different aspects of herbage production over the last ten years. This literature was reviewed and analysed to extract relevant herbage production data for the NCYCLE_IRL validation process. These studies addressed herbage production responses to different N fertiliser applications, soil types, regions, cutting regimes, reseeding times and different sources of N applied. However, only very few (e.g. Ryan, 1974[a,b], and Ryan, 1976) included more than two of these factors as variables.

2.5 An evaluation of the need to include urea as a fertiliser N type in NCYCLE_IRL.

A literature review was undertaken to determine if the application of urea rather than other N fertiliser types (calcium ammonium nitrate (CAN) or ammonium nitrate (AN)) was an important factor determining variation in the herbage yields thereby justifying its inclusion in NCYCLE_IRL model.

This review consisted of four subsections:

2.5.a Fertiliser N use – type.
2.5.b Main N-flow pathways following urea applications to the soil.
2.5.c Impact of urea fertilisation on herbage productions in Ireland.
2.5.d Conclusions.

2.5.a Fertiliser N use - type

The 2002 Irish Fertiliser Use Survey (Coulter *et al.,* 2002) reported that most farms (40%) used CAN for grazed grasslands and the high N compounds (e.g., 23:2.5:5) for silage production (49 %). Urea accounts for about 17 % of N fertiliser used on Irish grassland.

2.5.b Main N-flow pathways following urea applications to the soil

Multiple interactions and processes occur following the application of urea to the soil. A simplification of the N flow pathways is shown in Figure 2.15.

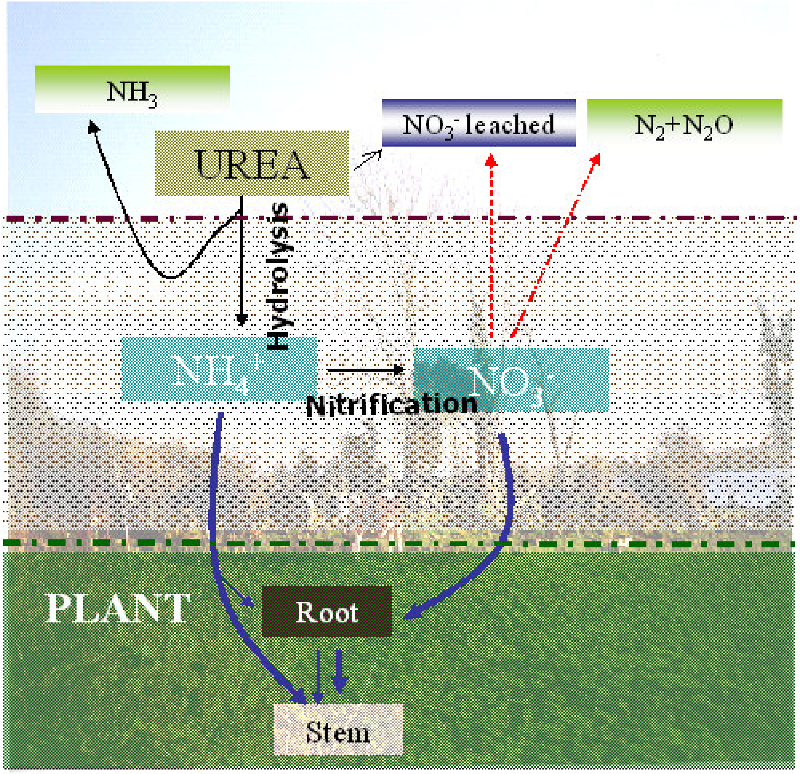


Figure 2.15. A simplified sketch of the main pathways and transformations of urea-N between the plant-soil-atmosphere

The main pathways studied in this subsection are

(i) Hydrolysis of urea.
(ii) Leaching of urea.
(iii) Volatilisation of urea.
(iv) N uptake by the plant.
(v) Nitrification.
(vi) Denitrification and N leaching.

(i) Hydrolysis of urea: Urea is hydrolysed by the enzyme urease and the rate of this catalytic reaction depends on several factors such as: soil organic carbon (C) content, cation exchange capacity (CEC), temperature, pH, moisture level and urea concentration in the soil. Generally it follows Michaelis-Menten kinetics; that is, the hydrolysis rate increases with increasing substrate concentration until the enzyme is saturated. Normally hydrolysis increases with increasing temperature (according to the Arrhenius equation) and has an optimum pH range of 7 to 9. The effect of soil moisture levels is unclear.

O'Toole *et al.* (1982) investigated levels of urease activity in Irish soils. The levels of urease activity were correlated with total-N, texture, CEC, pH and C/N ratio. Over 50 % of the variation in urease activities was found to be associated with variations in soil organic matter and texture. The calculated times for complete urea hydrolysis were, on average, 43 hours at 24^{o}C, 71 hours at 16^{o}C and 148 hours at 8^{o}C.

(ii) Leaching of urea: Apart from hydrolysis, urea can also be leached below the root system. In winter if urea hydrolysis is delayed (low organic matter, low pH and cold temperatures) and if the rainfall rate is high, urea may be transported down the soil profile below the root system.

(iii) Volatilisation of urea: Following the application of urea to the soil it is adsorbed onto the soil as NH_4^+ or volatilised as ammonia (NH_3). The NH_4^+ has to be converted into NH_3 before volatilisation can occur. The NH_3 volatilisation rate is controlled by the rate of removal and dispersion of NH_3 to the atmosphere. This rate is affected by (a) environmental factors such as temperature, wind speed, rainfall and atmospheric NH_3 concentration, by (b) soil factors such as buffer capacity, infiltration rate, pH, CEC and by (c) agronomic factors such as the amount and N concentration of the applied urea fertiliser.

Ammonia volatilisation is affected mainly by an enzymatic reaction: hydrolysis and a physical reaction: transport of NH_3 to the atmosphere. The same factors can influence both hydrolysis of urea and the transport of NH_3 in either direction which can make prediction of NH_3 losses difficult. For instance, rainfall tends to enhance hydrolysis by adding water to the topsoil, which allows the urea to dissolve and hydrolyze (Bouwmeester *et al.,* 1985). This increases the potential for NH_3 volatilisation. On the other hand, rainfall tends to enhance soil adsorption of the NH_4^+ ion thereby decreasing potential NH_3 losses. The latter seems to take place if the rainfall event is intensive or relatively long.

Conditions of light precipitation that provide moisture adequate for urea hydrolysis but insufficient to leach urea result in greatest NH_3 losses (Craig and Wollum, 1982). The key point at this stage seems to be the dynamics of vertical transport of urea and thus adsorption or leaching into the soil and the rate of hydrolysis.

In general, losses of NH_3 from urea application can vary from 0.4 to 80 % of the applied urea-N. Nevertheless, in Ireland O'Toole and Morgan (1983) reported potential NH_3 losses ranging from 0.3 % to 9.3 % of the applied urea-N. The extent of NH_3 volatilisation from different soils was determined by buffering capacity and pH. Well-buffered soils will tend to immobilise NH_4^+ and the risk of NH_3 loss will be minimal. In contrast, with soils having lower CEC values (less well-buffered) NH_3 loss can be of significant importance. Soils with high clay content and organic matter will tend to have a higher buffering capacity and thus, produce less NH_3. O'Toole and Morgan (1983) proposed a critical CEC value of < 250 me kg^{-1} below which NH_3 losses from urea can be significant. About 52 % of Irish soil series have CEC values less than the proposed critical CEC value.

Seasonally, the risk of NH_3 loss is greatest in summer as higher temperatures will increase hydrolysis and the transport of urea into the soil will be reduced by low soil water content (O'Toole and Morgan, 1983). The transport by rainfall will be effective on dry soils only if it occurs within three days of fertiliser application. O'Toole and Morgan (1983) also indicated that the potential risk of substantial NH_3 losses is likely to be highest in the east and south-east of Ireland as the climate in these areas is warmer and drier than in other regions.

(iv) N uptake by the plant: The NH_4^+ that has been adsorbed by the soil (or immobilised), will be nitrified by bacteria or be absorbed by the plant. Plants actively absorb both soil NH_4 and NO_3 from the soil water. The preferential uptake of one form or the other is affected by many soil and environmental factors.

The predominant N-form available to plants is NO_3 since under most soil conditions NH_4 is rapidly nitrified to NO_3. The utilization of NO_3 by plants involves several processes, including uptake into the plant, storage into vacuole, translocation to the shoot, reduction into NH_4 and incorporation of N into organic forms. Some species reduce great quantities of NO_3 in their roots whereas others translocate most of it to the shoot where it is reduced. The NH_4 is the major form of N available to plants under conditions that are unfavourable for nitrification (e.g., poor aeration, soil acidity or cold temperatures). It cannot accumulate in cells as it is toxic to the plant and is normally converted to amino acids or amides in the root and translocated to the shoots in these organic forms.

Nitrate uptake seems to be repressed by NH_4^+ in some cases and species. In the majority of cases, NH_4 appears to have an inhibitory effect on NO_3 uptake that is independent of any such effect on NO_3 reductase enzyme activity. Temperature also appears to exert an influence on some species and under some conditions on preferential NH_4 uptake.

The effect of root temperature on the uptake of N and the size of the root system was investigated by Clement *et al.* (1978), Clarkson and Warner (1979), Clarkson *et al.* (1986), Watson (1986) and MacDuff and Jackson (1991). These studies investigated the preferential N-form uptake by plants and the factors affecting it. Watson (1986) indicated that NH_4 is preferred as the N-form compound by ryegrass grown in soil, under controlled simulated spring conditions at all ranges of temperatures, but especially when soil temperatures are low. The limited uptake of NO_3 appeared not to be due to an inhibitory effect of the NH_4 ion. Ryegrass not only absorbed less N from NO_3 but also translocated a lower percentage of the total N to the shoots. Clarkson and Warner (1979), studying ryegrass grown in solution culture detailed the preference for NH_4 from cold soils and found similar results. Thornley (1998), proposes an equation to allow for the relative rate of uptake from the NH_4 and NO_3 pools which varies with temperature. Relative NO_3 uptake ranges 0 to 1, increasing linearly from 0 to 20 ^{o}C, respectively.

These studies also indicated the complexity of these mechanisms, the plant species dependence and pinpointed the necessity for further study in order to give predictions. The key point would be the intensity with which the plant is competing for the NH_4 or NO_3, as influenced by a varied range of factors, temperature being the most important but not the only one.

(v) Nitrification**:** Nitrification by autotrophic bacteria populations will also compete for the NH_4 in the soil. Nitrification in the soil has been thoroughly studied and is believed to follow zero or 1st-order kinetics. Many studies have pointed out the importance of temperature, moisture and pH on the rate of nitrification.

(vi) Denitrification and N leaching: The NO_3 that has not been absorbed by the plant is prone to be lost either by denitrification or by leaching.

2.5.c Impact of urea fertilisation on herbage production in Ireland

Many Irish studies investigated the effect of fertiliser N type and season of application on herbage production. For example, Collins (1969), Murphy (1969) and Keane *et al.* (1974) found no difference between three N sources (CAN, AN, urea) applied at the same rate on either first harvest or total annual yields.

Herlihy (1980) compared the efficiency of urea and CAN for grass silage production at two sites (Johnstown Castle – loam; and Oakpark - coarse sandy loam). Herbage production was measured in spring – early grass, for first-cut silage and mid-late season silage cut. The conclusions were as follows:

1. *Early grass:* In general there was no effect of fertiliser N type on grass production.
2. *Fist-cut silage*: In general, there was no effect of fertiliser N type on grass production.
3. *Mid-late season silage*: Grass production was higher from the CAN compared with the urea treatment. Probably, the low soil moisture and higher temperatures at this time resulted in elevated NH_3 losses from the urea.

The results are also summarised in Figure 2.16. On average, herbage DM yields and N offtakes were generally higher for the CAN treatment compared with urea. The difference was generally less than 10 % and in two cases yields were very similar (Johnstown Castle -78 and Oakpark-77). During the driest and hottest years, the differences tended to be highest, favouring the application of CAN. Dry matter yields and N offtakes were similar for the two fertiliser types in the colder and wetter years.

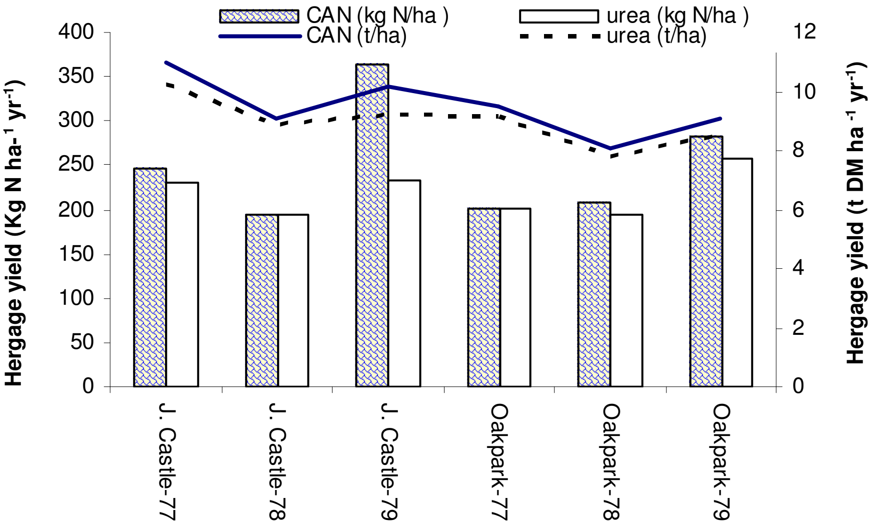


Figure 2.16. Annual herbage dry matter yields (t ha^{-1}) and N offtakes in herbage (kg ha^{-1}) for grasslands fertiliser with either CAN or urea for three years at two sites (J. Castle and Oakpark) (After Herlihy, 1980).

Herlihy *et al.* (1987) analysed plant response to urea and CAN in spring (following January and February applications). The variation in the direct effect was described by models that included temperature and long-term rainfall for CAN and, additionally, short-term rainfall for urea. The fitted equations suggested that whereas herbage DM yield in urea-fertilised grassland was related to temperature, long-term rainfall and short-term rainfall, it was only related to temperature and long-term rainfall in grasslands fertilised with CAN. The efficiency of urea was comparable to CAN in most of the results. Herbage DM in urea-fertilised grasslands was greater than herbage DM in CAN-fertilised grasslands, when the weather was cold and wet.

In Northern Ireland, Stevens *et al.* (1989) analysed the effect of application date and N fertiliser type on spring herbage production. They reported a DM yield increase of between -0.6 to 1.1 t ha^{-1} with urea compared with CAN. The following trends were found for spring herbage production:

- When DM was low (0-2 t ha^{-1}) the response to CAN was greater than urea
- When DM was average (2-3 t ha^{-1}) the response to CAN was similar to urea
- When DM was high (>3 t ha^{-1}) the response to CAN was smaller than urea

In other crops, Gately (1994) compared the efficiency of urea and CAN, applied to winter wheat, and concluded that grain-protein content was significantly lower with urea rather than with CAN use.

Evidence may suggest, therefore, that urea fertilisation could result in some cases in lower herbage yields and thus, probably higher N losses. Application of urea to grasslands during the driest and hottest months of the year seems to result in lower N fertiliser efficiency. Currently, best practice discourages farmers from using urea during late spring and summer.

2.5.d Conclusion

A small but significant percentage of Irish farms currently use urea as the main N fertiliser option (17 %) (Coulter *et al.,* 2002). However, predicting its efficacy in terms of grass production can be difficult and probably is not appropriate in a simple model with an annual time step that does not account for the NO_3 and NH_4 pools separately.

Prediction of NH_3 transformations requires a very short time-step and accurate wind and daily climatic information. The possibility of introducing an emission factor has been proposed by Hyde *et al.* (2003), who suggest that 23 % of the urea applied would be volatilised as NH_3. However, this ignores the actual field variation that occurs in response to climate, soil types and managements.

The studies reviewed generally indicate a poorer herbage DM response when using urea throughout the season. Nevertheless, the effect was generally not greater than 10 % and sometimes no difference was recorded. However, in practical farm circumstances the preferential use of urea in spring rather than summer, based on good practice, implies yield decreases as a consequence of its use rather than CAN are negligible. Therefore, the inclusion of urea fertiliser as a factor in NCYCLE_IRL was not considered necessary.

2.6 Updating with new functions for animal production and excreta N division and producing a new NH_3 generator submodel

This section was divided into two subsections:

- 2.6.a Animal production and excreta division.
- 2.6.b Defining a new NH_3 generator submodel

2.6.a Animal production and excreta N division

Cattle diet manipulation has been regarded as a very important means to improve the efficiency of N utilisation. In the last decades, many changes have been made to improve animal N efficiency including breed and diet changes. Animal science has also provided new approaches to investigate the effect of different feeding strategies on dairy milk production. The approaches used in the original NCYCLE were tested and compared with the newer approaches (e.g., Kebreab *et al.,* 2001; Moorby, 2003).

Scholefield *et al.* (1991) proposed that for dairy cows, N in milk was 23 % of the total N intake by the dairy cow and the distribution of excreted N between dung and urine reflected the N concentration of the diet. The model used the approaches for beef cattle from Henzell and Ross (1973), Van der Meer (1982) and Betteridge *et al.* (1986). The relationship is linear over the range considered and it predicts that, with 1.5 % N in the diet, 45 % of the excreted N occurs in the urine, whereas with 4 % in the diet, 80 % occurs in the urine.

In recent studies, Kebreab *et al.* (2001) analysed the amount and form of N excreted under different dairy cattle production systems. To estimate the relationship between N intake (g N day^{-1}) and excretion (g N day^{-1}), experiments were conducted using similar diets but with different levels of protein. The mathematical representations of the relationships were as follows:

$N_{\text{dairy cow dung}} = 0.15 * N_{\text{Animal Intake}} + 78$ $(R^2 = 0.53)$ **(2)**

$N_{\text{dairy cow milk}} = 0.17 * N_{\text{Animal Intake}} + 34.8$ $(R^2 = 0.90)$ **(3)**

$N_{\text{dairy cow urine}} = 0.0052 * (N_{\text{Animal Intake}}^{1.7})$ $(R^2 = 0.95)$ **(4)**

$N_{\text{dairy cow excreta}} = N_{\text{dairy cow urine}} + N_{\text{dairy cow dung}}$ **(5)**

They also found that, while at lower or medium N intake the urinary N output was similar in starch and fibre-based diets, higher N intake is better utilised in the former. The mathematical representations of the relationships were as follows :

Starch-based diet

$N_{\text{dairy cow dung}} = 0.31 * N_{\text{Animal Intake}} + 30.9$ $(R^2 = 0.82)$ **(6)**

$N_{\text{dairy cow urine}} = 0.25 * N_{\text{Animal Intake}} - 0.72$ $(R^2 = 0.41)$ **(7)**

Fibre-based diet

$N_{\text{dairy cow dung}} = 0.28 * N_{\text{Animal Intake}} + 32$ $(R^2 = 0.74)$ **(8)**

$N_{\text{dairy cow urine}} = 0.30 * N_{\text{Animal Intake}} - 0.70$ $(R^2 = 0.61)$ **(9)**

Moorby (2003) reviewed literature on dairy cow dietary N efficiency. He investigated the reasons for the inefficiencies in the use of dietary N that were resulting in elevated N excretion levels. The review identified that N utilisation efficiency of UK dairy cattle is typically in the range 20-30 %. Mathematical representations were derived from literature showing the relationship between N intake (g N day^{-1}) and N amount (g N day^{-1}) and form excreted as follows:

$N_{\text{dairy cow dung}} = 0.16 * N_{\text{Animal Intake}} + 66.6$ ($R^2 = 0.33$) **(10)**

$N_{\text{dairy cow urine}} = 0.66 * N_{\text{Animal Intake}} - 108$ ($R^2 = 0.70$) **(11)**

$N_{\text{dairy cow milk}} = 0.056 * N_{\text{Animal Intake}} + 89.8$ ($R^2 = 0.06$) **(12)**

Comparisons were made to compare simulated NCYCLE_IRL results obtained using the original functions with those proposed by Kebreab *et al.* (2001) using the Moorby (2003) data (Figures 2.17, 2.18 and 2.19).

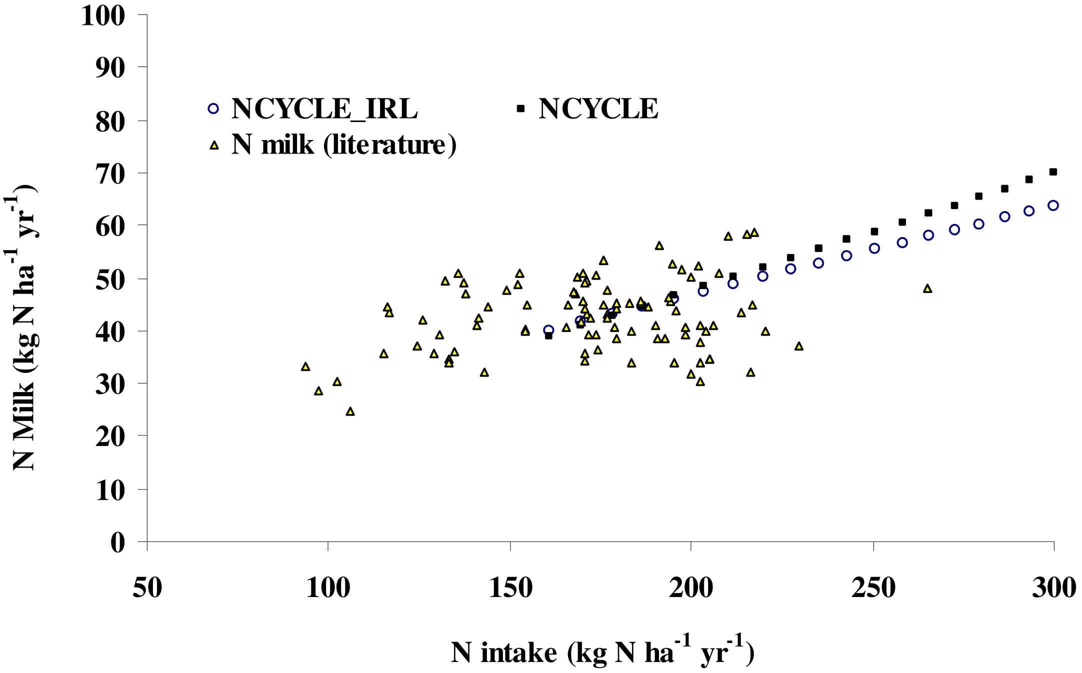


Figure 2.17. Comparison of literature, NCYCLE and NCYCLE_IRL values of N in milk over a range of N intakes (kg N ha^{-1} yr^{-1})

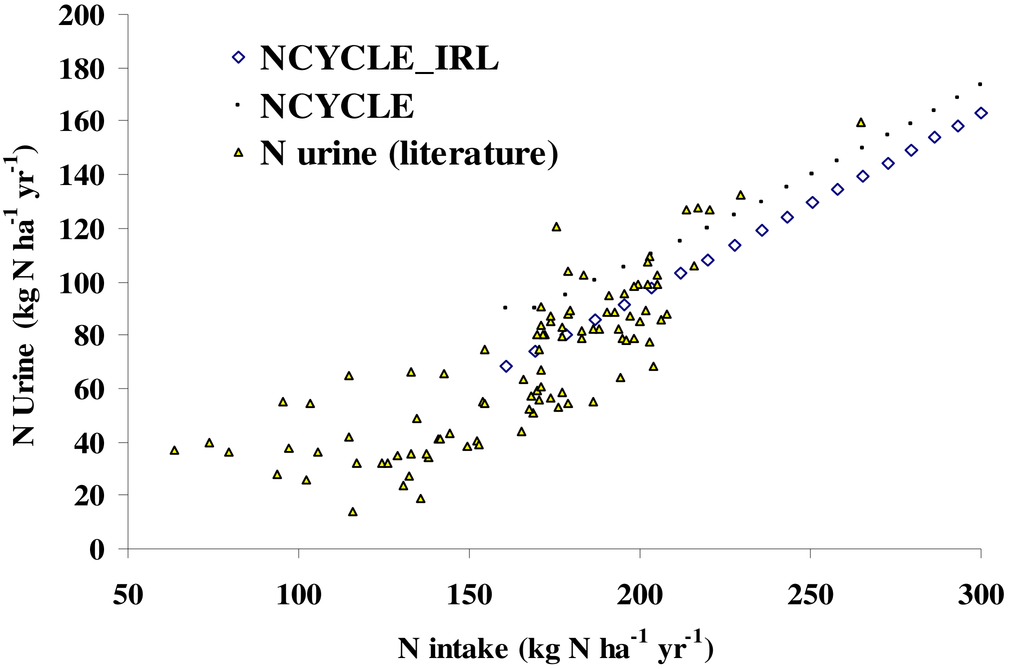


Figure 2.18. Comparison of literature, NCYCLE and NCYCLE_IRL values of N in urine over a range of N intakes (kg N ha^{-1} yr^{-1})

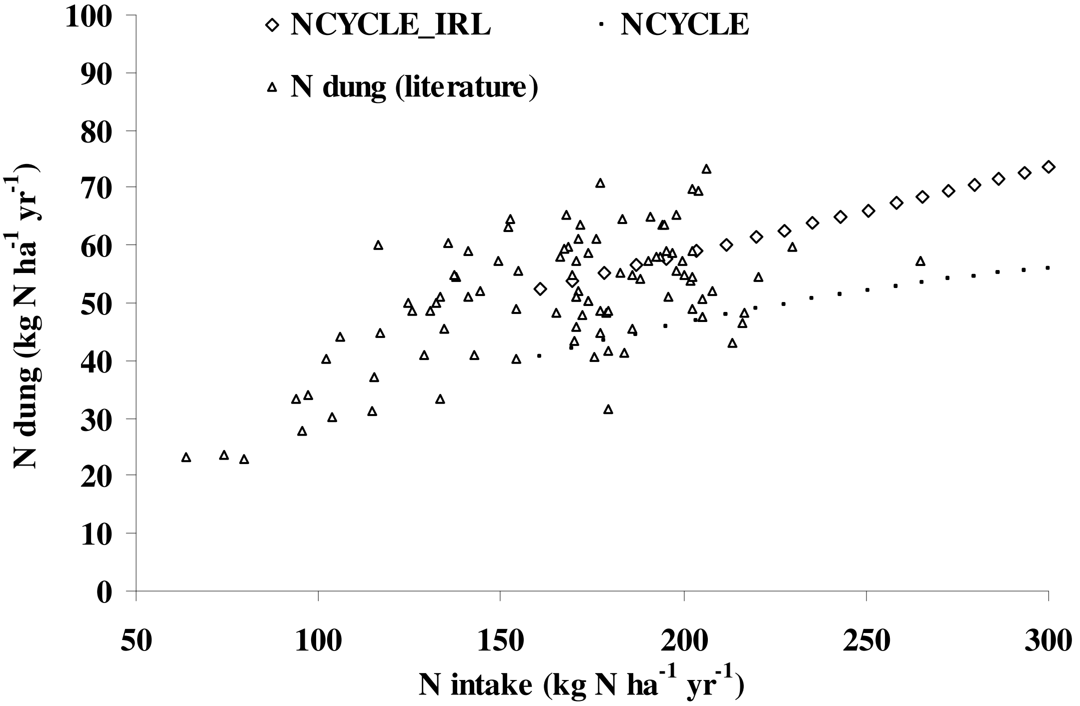


Figure 2.19. Comparison of literature, NCYCLE and NCYCLE_IRL values of N in dung over a range of N intakes (kg N ha^{-1} yr^{-1})

The results indicate that both NCYCLE and NCYCLE_IRL predict values within the literature range reported by Moorby (2003). On the other hand, NCYCLE tends to slightly over-predict urine N and under-predict dung N compared with the reported literature values. NCYCLE uses functions that consider the protein to energy ratio in the dairy cow feed intake (% N in the herbage). Intensive farms normally use feed concentrates or supplements with different protein to energy ratios which explains the over estimate urine N by NCYCLE. To address this, the relationships proposed by Kebreab *et al.* (2001) were adopted, which relate quantities and forms of excretion to total N intake and averages the protein to energy ratio during the grazing period.

The between farm variability in dairy cow feeding regimes is high. Hence, the feeding systems themselves contribute to level of uncertainty and variability in the outputs of a dairy farm. Therefore, there is scope for improving the predictions of N flows for a dairy farm by developing a more appropriate feeding module which can reflect the effect of feed quality on the N retention and excretion.

Against this background, the current dairy cow performance is best simulated by the Kebreab *et al.* (2001) approach: the total N in milk (kg N ha^{-1} yr^{-1}) is calculated as follows:

$$N_{\text{dairy cow excreta}} = 0.17 * N_{\text{Animal Intake}} + 12.702 \quad \textbf{(13)}$$

$$N_{\text{dairy cow milk}} = N_{\text{Animal Intake}} - N_{\text{dairy cow excreta}} \quad \textbf{(14)}$$

The proportion of the N in the herbage that is transformed to live-weight gain for beef farms is similar to that used in NCYCLE (Scholefield *et al.,* 1991). The proportion of the N in the herbage that is transformed to live-weight gain is related to the herbage N concentration based on a relationship derived from ARC, (1980). The total N beef product (kg N ha^{-1} yr^{-1}) is calculated as follows:

$$N_{\text{beef product}} = N_{\text{Animal Intake}}*((6.357 + 51.268*0.47143^{\text{Percent N Diet}})*0.01) \quad \textbf{(15)}$$

Steen and Laidlaw, (1995), Ireland, found a live-weight gain per hectare increase of 20.5 % and 22.5 % by applying 360 kg N ha^{-1} yr^{-1}comapred with 60 kg N ha^{-1} yr^{-1} in a high stocking rate and a low stocking rate grassland, respectively. The model NCYCLE_IRL predicts that, on average, for this particular situation and for zone 4 (Galway area) and for a clay loam soil, a N liveweight gain of 21.7 % is obtained when comparing a grazed beef grassland fertilised with these two fertiliser rates.

2.6b Refining the NH_3 generator sub-model

Agriculture is considered to be the principal source of NH_3 emissions in Ireland. It accounted for 90 % or the emission of 130 kt in 1998 (Humphreys *et al.,* 2003). Under the objectives of the Gothenburg Protocol and the national Emissions Ceiling Directive (2001/81/EC), target emissions of NH_3 from Irish agriculture are 116 k t by 2010.

Some studies on NH_3 emissions from animal excreta were reviewed to determine if the factor of 15% for the proportion of the urine-N volatilised used in the original NCYCLE required updating. This was based on the mean value obtained from experiments using wind tunnels (e.g. Ryden *et al.* (1987), Vertregt and Rutgers (1987) and Lockyer and Whitehead (1990 b). In the model, this proportion can also be altered manually by the user. The proportion of dung-N volatilised was assumed to be 3 %, based on the results of MacDiarmid and Walkin (1972) and Ryden *et al.* (1987).

Other studies indicate that between 4 to 41 % of the N from applied cattle urine may volatilise (Ball and Ryden, 1984; Lockyer and Whitehead, 1990 b; Ryden *et al.,* 1987; Vallis *et al.,* 1982; Vertregt and Rutgers, 1987; Whitehead and Raistrick, 1993) with an extreme of 66 %. Results for dung ranged from 1-13 % (MacDiarmid and Walkin, 1972; Sugimoto and Ball, 1989; Vertregt and Rutgers, 1987; Ryden *et al.,* 1987).

In NCYCLE_IRL two relationships were incorporated as an additional refinement to the existing NCYCLE submodel. The fraction of excreted N lost as NH_3 (Vfrac) is related to the average dietary N concentration (ND: g kg^{-1} DM) as follows:

For dairy cows: $\text{Vfrac} = 2.717\ 10^{-7} * \text{ND}^{3.389}$ (Bussink, 1996) **(16)**
For beef cows: $\text{Vfrac} = 1.267\ 10^{-4} * \text{ND}^{1.853}$ (Jarvis *et al.,*1989) **(17)**

Simulated NH_3 losses from excreta predicted for a range of N fertiliser applied, for dairy and beef systems and using the auto and the manual mode (using the following settings – Zone 1, long-term grassland, sward age – 4 to 6 years and a moderately drained loam soil) are shown in Figure 2.20.

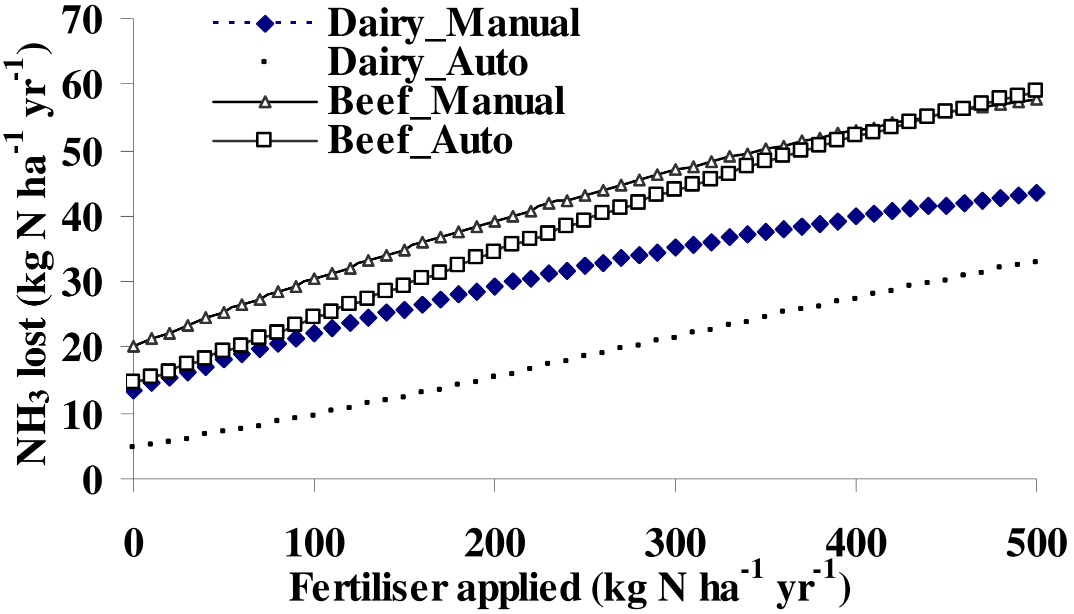


Figure 2.20. Predictions of NH_3 losses from excreta from beef and dairy animals using an emission factor of 15 % and 3 % for the urine and dung, respectively, (manual) and by using the new incorporated functions (auto)

In the case of beef animals, predictions made by using the auto and the manual mode appear to agree quite well within the range of fertiliser applied. However, for dairy cattle, the function of Bussink (1996) appears to produce much lower NH_3 losses than those predicted using the NCYCLE default values of 15 % and 3 % for the urine and dung, respectively.

2.7 Producing the new denitrification and leaching submodel

The original NCYCLE model calculated the total N lost through denitrification and leaching as the difference between the inputs to the soil inorganic N (fertiliser, atmosphere, mineralisation, urine, dung and dead plant material) and uptake by the plant component in the sward + NH_3 volatilisation from urine and dung (Scholefield *et al.,* 1991). The proportion of the remaining loss attributable to denitrification is then derived according to soil texture and drainage class from the matrix in Table 2.3, which is based on Scholefield *et al.* (1988). Leachable N is then obtained by difference.

For NCYCLE_IRL, the same factors were used because the denitrification and leaching mechanism proposed by NCYCLE suggests that the main differences in the splitting are based on physical properties of the soil (universal factor), which indirectly influence the denitrification process rate by influencing the capacity of different kinds of soil to retain water and thus alter the redox potential. Temperature, indirectly is accounted for when selecting different Irish agroclimatic zones. The temperature influences the quantity of N that flows in the soil and thus the amount of total N subject to denitrification or leaching losses.

Table 2.3. Relative denitrification rates, expressed as a fraction of denitrification plus leaching, as a function of texture and drainage.

	Drainage		
Texture	**Good**	**Moderate**	**Poor**
Loam	0.25	0.45	0.65
Sandy Loam	0.15	0.3	0.55
Clay Loam	0.3	0.55	0.75
Peat*	*0.3*	*0.55*	*0.75*

*Factors for peat texture are for testing and are not derived from data.

NCYCLE_IRL was upgraded to produce estimates of the N leached per hectare with peak and average N concentrations in the leachate. This was based on information from Scholefield *et al.* (1993), Scholefield *et al.* (1996*)* and Rodda *et al.* (1995). In these studies, relationships between the load of leached N and its concentration in drainage water were derived. Wholly empirical relationships between NO_3 load, NO_3 concentration and the volume of drain flow were used to predict the outcome of preferential flow, so that for a given drainage volume and a given soil texture, which are supplied by the user, the percentage of soil N that is actually leached can be calculated. Well-fitted linear regressions of peak NO_3 concentration on total leached soil NO_3 were obtained for soils of different texture under grassland management. The relationship between average NO_3 concentration and total NO_3 load was found not to be influenced by differences in soil texture but could also vary depending on differences in drainage conditions. Average NO_3 concentration was defined as the total amount of NO_3 leached divided by the drainage volume.

2.8 Coding the main model and interface in DELPHI 5

The original NCYCLE was first incorporated into a PASCAL program for IBM-compatible PC machines (Lockyer *et al.,* 1990 a). All the code for NCYCLE_IRL was programmed in DELPHI 5.

The program consists of five units (NCYCL_IRL*, InitUnit, Flow_DiagramUnit, GraphUnit* and *Aboutversion*) and three forms (*Form1, Form2, Form3*):

The *NCYCLE_IRL* unit enables the user to enter all the variables from the screen that can be changed by events such as: clicking on spin edits (numbers), selecting on checking radio buttons (different possibilities within a range), clicking on three different maps (or three different panels) or clicking on a menu tool bar. This piece of code also enables the model to show all the results in text boxes.

In the *InitUnit* unit, the types, variables and constants used in the program are declared in the interface section of the unit. Arrays are also declared and filled with values in the implementation section of the unit.

In the *Flow_DiagramUnit* unit all the N pools are calculated. First, the program calculates the initial soil inorganic N pool by starting the soil mineralisation submodel (soil-mineralised N dependent on type of soil, drainage, sward age, grassland history and location) and adding the estimate to the N inputs from fertilisation In the next step, the model loops and starts calculating the N and DM yield in the herbage and the plant N uptake. When the model is simulating a cut field, the N and DM yield in the herbage will be considered as a product and the rest of the N taken up by the plant will enter a submodel for mineralisation of roots and debris.

When the model is simulating a grazing field, the herbage N is ingested by the animal and a portioned in assigned to product (as milk or meat) with the remainder excreted (as urine and dung). The N in the herbage not removed by the grazing animal together with N in the dung is allocated to the mineralisation submodel.

The plant N and dung N mineralised (and not volatilised) enters the pool of inorganic N, thus enabling the model to make the looped calculations. Once the exit criteria of this loop are met, N surplus is calculated and denitrified and leached N is derived. This unit also enables the model to simulate the field for a range of fertiliser N inputs from zero to 500 kg ha^{-1} yr^{-1}, producing text files (for every 10 kg N ha^{-1}) and a graph with all the results.

The units *GraphUnit* and *Aboutversion* are only used to store the graphs and the version number, respectively.

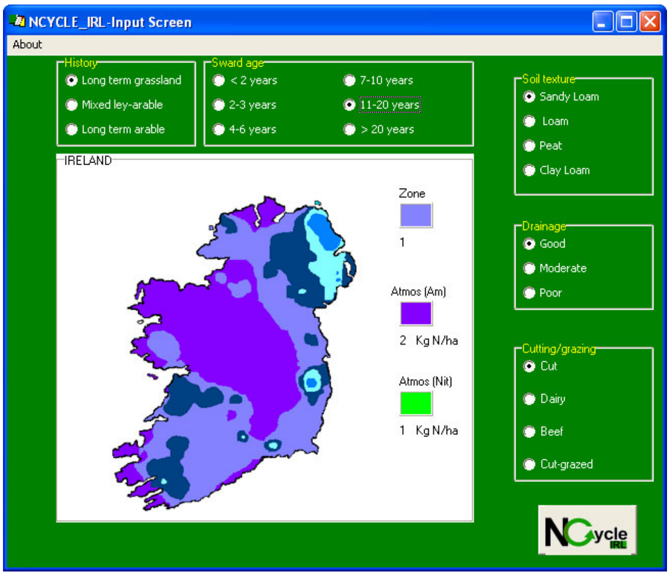
The interface consists of three forms (screens). The first form or screen is the input user (Figure 2.21). It allows the user to input data as

- History (long-term grassland, mixed-ley arable, long-arable),
- Grassland management system (cut, beef grazed, dairy grazed, mixed cut-grazed), sward age (<2, 2-3, 4-6, 7-10, 11-20, >20),
- Soil texture (sandy loam, loam, peat, clay loam) and

- Drainage class (good, moderate, poor).

The user can select them by clicking on the option buttons. The same screen has three maps of Ireland with information on NO_3^--N atmospheric deposition, NH_4^+-N atmospheric deposition and grass agroclimatic areas or zones. By clicking on any area of the map, the user selects a site in Ireland that is already defined by these three factors. The model then activates the variables related to these factors.

The second screen or form is the N flow diagram (Figure 2.22). The user can investigate the fate of the annual N flows for a specified grassland site. The model displays N flows in kg ha^{-1} yr^{-1}, DM yield in t ha^{-1} yr^{-1} and annual peak, initial 25 mm and mean N concentration in the leachate in mg l^{-1}. Three different spin edit buttons enable the user to change (i) the N fertiliser inputs, (ii) the proportion of plant N ingested by grazing animals based on grazing pressure (u factor) and (iii) the value for urine N volatilisation from the default value of 15 %



History
● Long term grassland
○ Mixed ley-arable
○ Long term arable

Sward age
○ < 2 years
○ 2-3 years
○ 4-6 years
○ 7-10 years
● 11-20 years
○ > 20 years

Soil texture
● Sandy Loam
○ Loam
○ Peat
○ Clay Loam

Drainage
● Good
○ Moderate
○ Poor

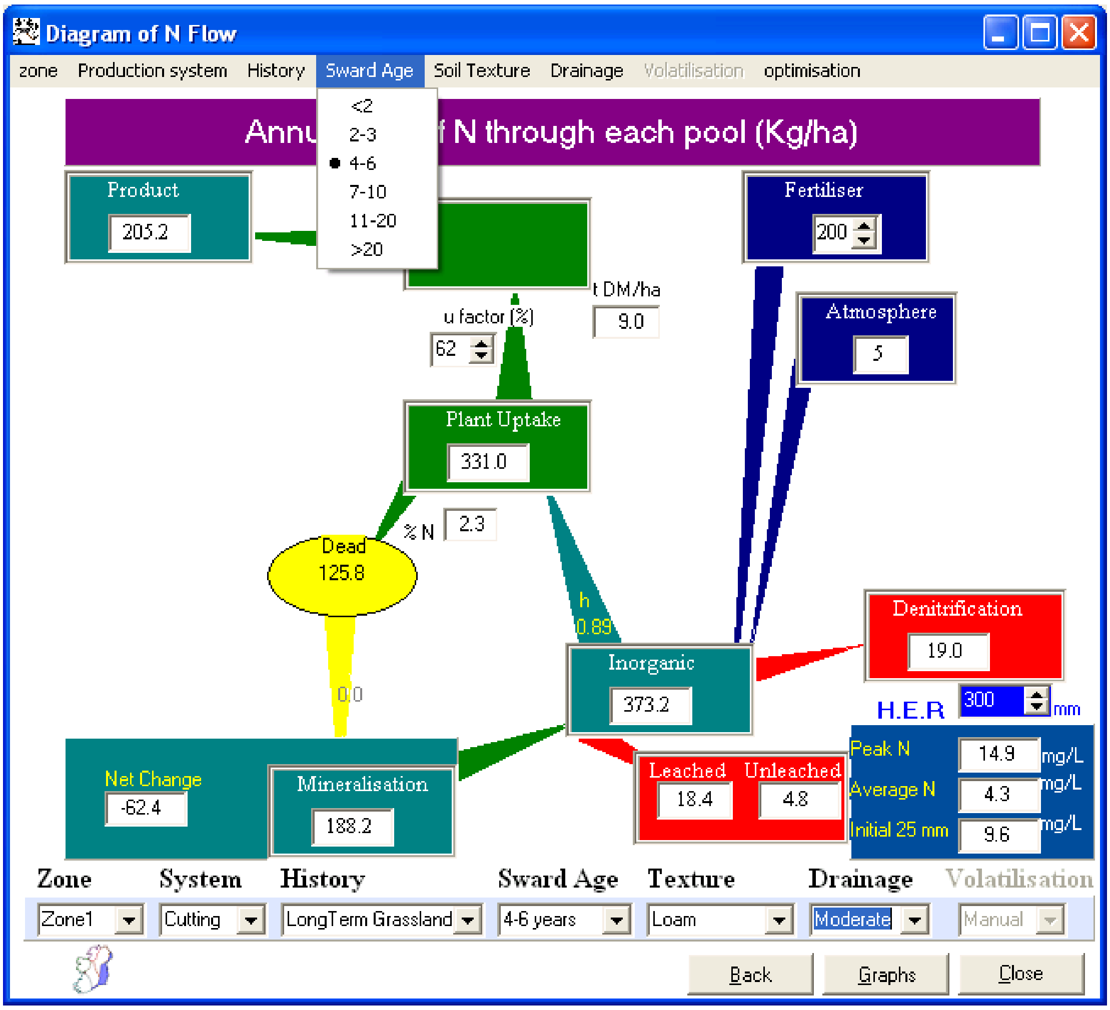
Cutting/grazing
● Cut
○ Dairy
○ Beef
○ Cut-grazed

Zone 1

Atmos (Am) 2 Kg N/ha

Atmos (Nit) 1 Kg N/ha

Figure 2.21. Input user screen of NCYCLE_IRL



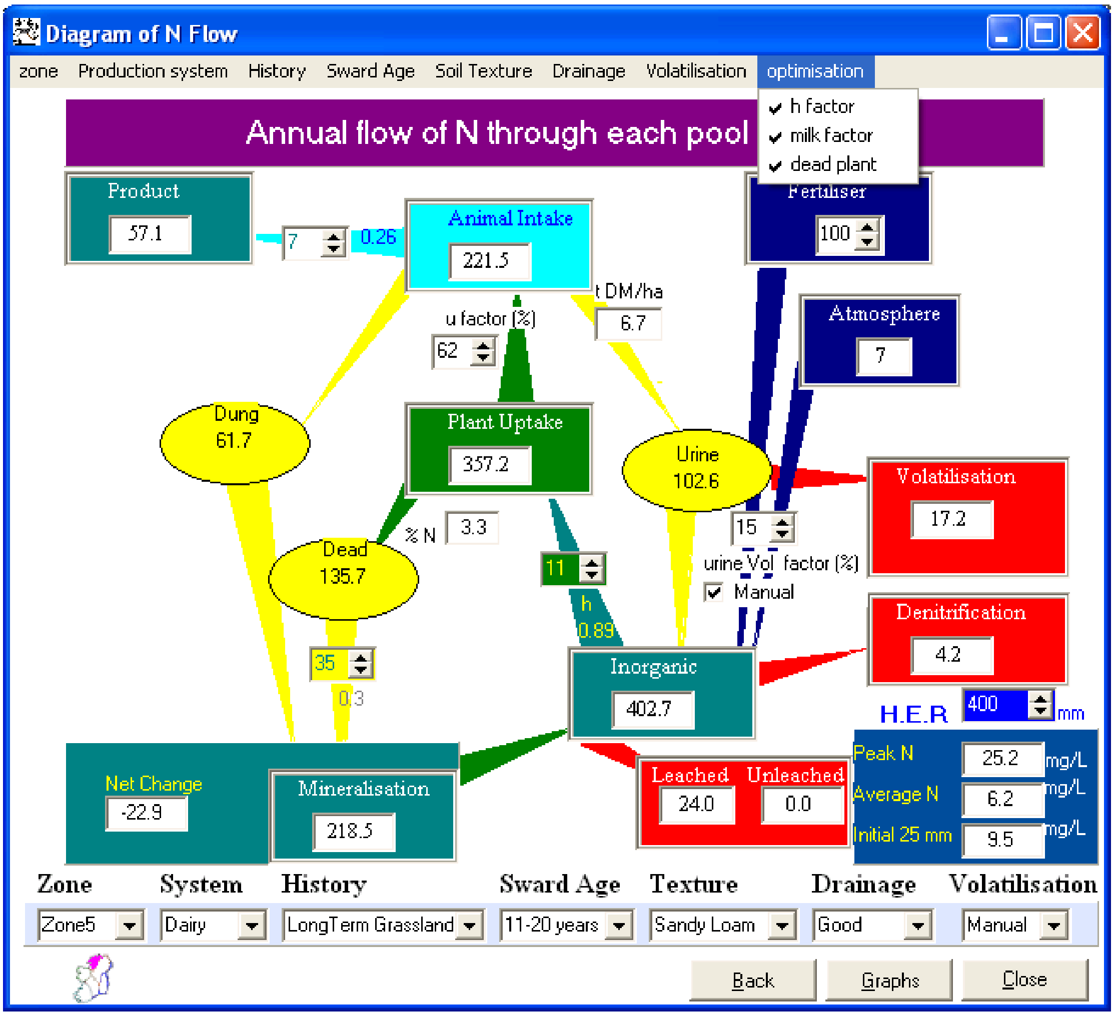
Product 205.2
Fertiliser 200
t DM/ha 9.0
Atmosphere 5
u factor (%) 62
Plant Uptake 331.0
% N 2.3
Dead 125.8
h 0.89
0.0
Inorganic 373.2
Denitrification 19.0
H.E.R 300 mm
Peak N 14.9 mg/L
Average N 4.3 mg/L
Initial 25 mm 9.6 mg/L
Leached 18.4
Unleached 4.8
Net Change -62.4
Mineralisation 188.2

Zone	System	History	Sward Age	Texture	Drainage	Volatilisation
Zone1	Cutting	LongTerm Grassland	4-6 years	Loam	Moderate	Manual

Figure 2.22. Diagram of N flows of NCYCLE_IRL

The user can change the factors such as Zone, System, History, Sward Age, Texture and drainage which will affect the simulation. Hydrologically effective rainfall can also be changed on this screen. The auto or manual NH_3 volatilisation modes can be selected by using this menu or by checking a button.

NCYCLE_IRL includes an optimised procedure to enable the user to manually explore the impact of changing different efficiency factors in the whole N cycle (h factor, partition into milk factor and dead plant mineralised factor) (Figure 2.23).



Product 57.1
7
0.26
Animal Intake 221.5
Fertiliser 100
t DM/ha 6.7
u factor (%) 62
Atmosphere 7
Dung 61.7
Plant Uptake 357.2
Urine 102.6
Volatilisation 17.2
15
urine Vol factor (%)
☑ Manual
%N 3.3
Dead 135.7
11
h 0.89
Denitrification 4.2
35
0.3
Inorganic 402.7
H.E.R 400 mm
Net Change -22.9
Mineralisation 218.5
Leached 24.0
Unleached 0.0
Peak N 25.2 mg/L
Average N 6.2 mg/L
Initial 25 mm 9.5 mg/L

Zone: Zone5
System: Dairy
History: LongTerm Grassland
Sward Age: 11-20 years
Texture: Sandy Loam
Drainage: Good
Volatilisation: Manual

Figure 2.23. Run with optimised h, milk, dead plant mineralised factors

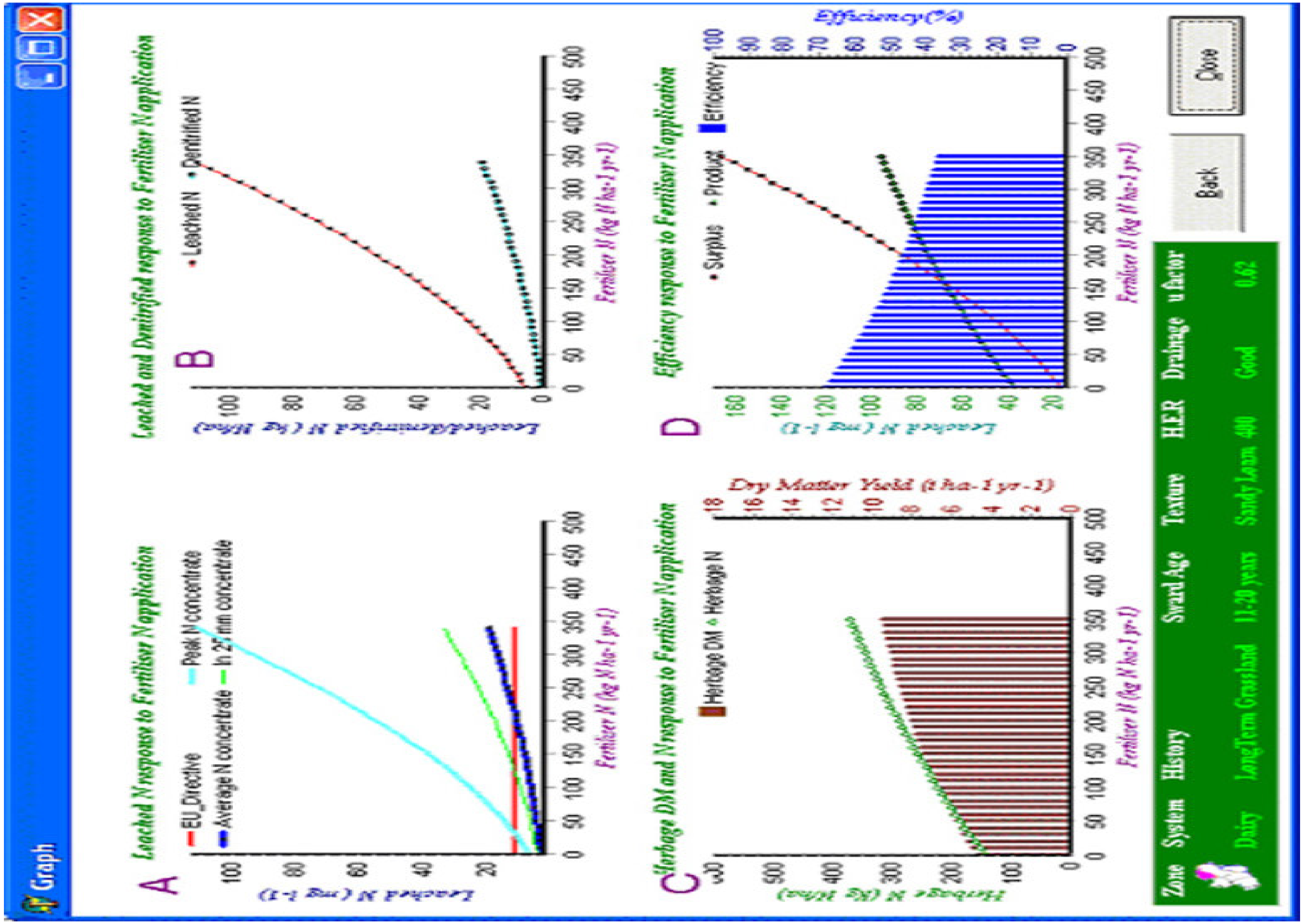
The third screen displays some simulated results from the selected scenario (Figure 2.24). Four types of graph are produced:

(i) ***Graph A*** - the NO_3-N concentration in leachate (average, initial 25 mm and peak) response to increasing fertiliser N inputs.

(ii) ***Graph B*** - the quantity of N leached and denitrified in response to increasing fertiliser N inputs.

(iii) ***Graph C*** - the herbage N and DM response to increasing fertiliser N inputs.

(iv) ***Graph D*** - the N surplus (denitrified, leached and volatilised N), N in product and efficiency in response to increasing fertiliser N inputs. Efficiency is expressed as the ratio between N product over N product + N surplus.



Zone	System	History	Sward Age	Texture	H.E.R	Drainage	u factor
	Dairy	LongTerm Grassland	11-20 years	Sandy Loam	400	Good	0.62

Figure 2. 24. Graphs interface in NCYCLE_IRL

2. 9 Validation of NCYCLE_IRL outputs

NCYCLE is an empirical model and therefore is partly validated by definition. No Irish study had the measurements for all the N pathways that would allow comparison with the model output. Nevertheless, some experimental measurements have been compared with NCYCLE_IRL output data.

- 2.9.a Herbage.
- 2.9.b Denitrification.
- 2.9.c Leaching.
- 2.9.d Effect of soil type on N losses.

2.9.a Herbage

The scenarios used to compare NCYCLE_IRL predictions of DM yields with measured DM data (Ryan 1974 [a,b]; O'Connell *pers. comm.)* are shown in Table 2.4. All scenarios were based on a reseeding time of more than two years and less than 11 years. The results are presented in Figures 2.25, 2.26 and 2.27. The model proved to be reasonably sensitive to agroclimatic zone and soil types. For instance, a moderately drained loam soil in the agroclimatic zone 6 (A-Ryan) resulted in up to 13 % more herbage DM yield than that in the agroclimatic zone 1 (D-Ryan).

Predicted herbage values on loam soils appear to agree quite well with observed data. This would be expected as there was a good variety of loam soils in the data-set used for the development of the NCYCLE_IRL herbage submodel. Herbage on sandy loam soils agreed well with two of the three sites. Herbage results from Moorepark grasslands were greater than those predicted by NCYCLE_IRL. There is no clear explanation for the discrepancy between the measured and predicted DM yields.

NCYCLE_IRL provided a good prediction of measured herbage yield on clay loam soils with poor and moderate drainage. However, herbage yield was over-estimated in well-drained soils (L-Ryan). This discrepancy could not be further investigated as there was only one site with this soil type and drainage classification.

Table 2.4. Situations simulated to compare predicted and measured herbage yields

Site	Site	soil texture	drainage
A-Ryan	*6*	Loam	Moderate
B-Ryan	*6*	Loam	good
D-Ryan	*1*	Loam	Moderate
E-Ryan	*1*	Loam	Moderate
L-Ryan	*1*	Clay Loam	Good
S-Ryan	*1*	Loam	Moderate
Q-Ryan	*4*	Sandy Loam	Good
R-Ryan	*4*	Sandy Loam	Moderate
T-Ryan	*3*	Clay Loam	Poor
U-Ryan	*3*	Clay Loam	Poor
Solohead	6	loam	Moderate
Kilmaley	6	clay loam	Poor
Ballyhaise	3	clay loam	Moderate
Ballinamore	2	clay loam	Poor
Moorepark	6	sandy loam	Good

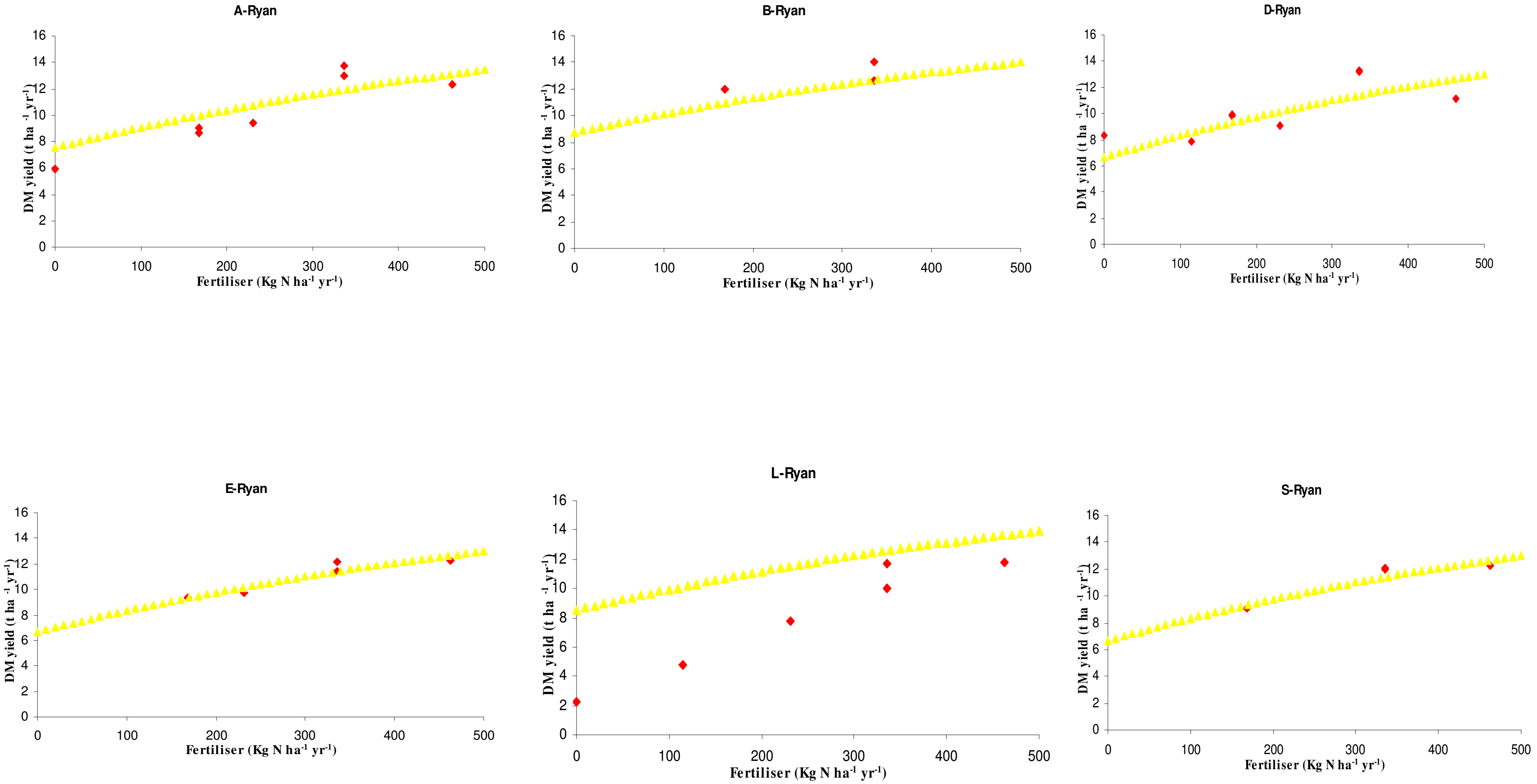


Figure 2.25. NCYCLE_IRL predictions and measured (Ryan 1974 [a,b])herbage dry matter yields (t ha^{-1}) in response to increases in fertiliser N inputs for sites A, B, D, E, L and S .

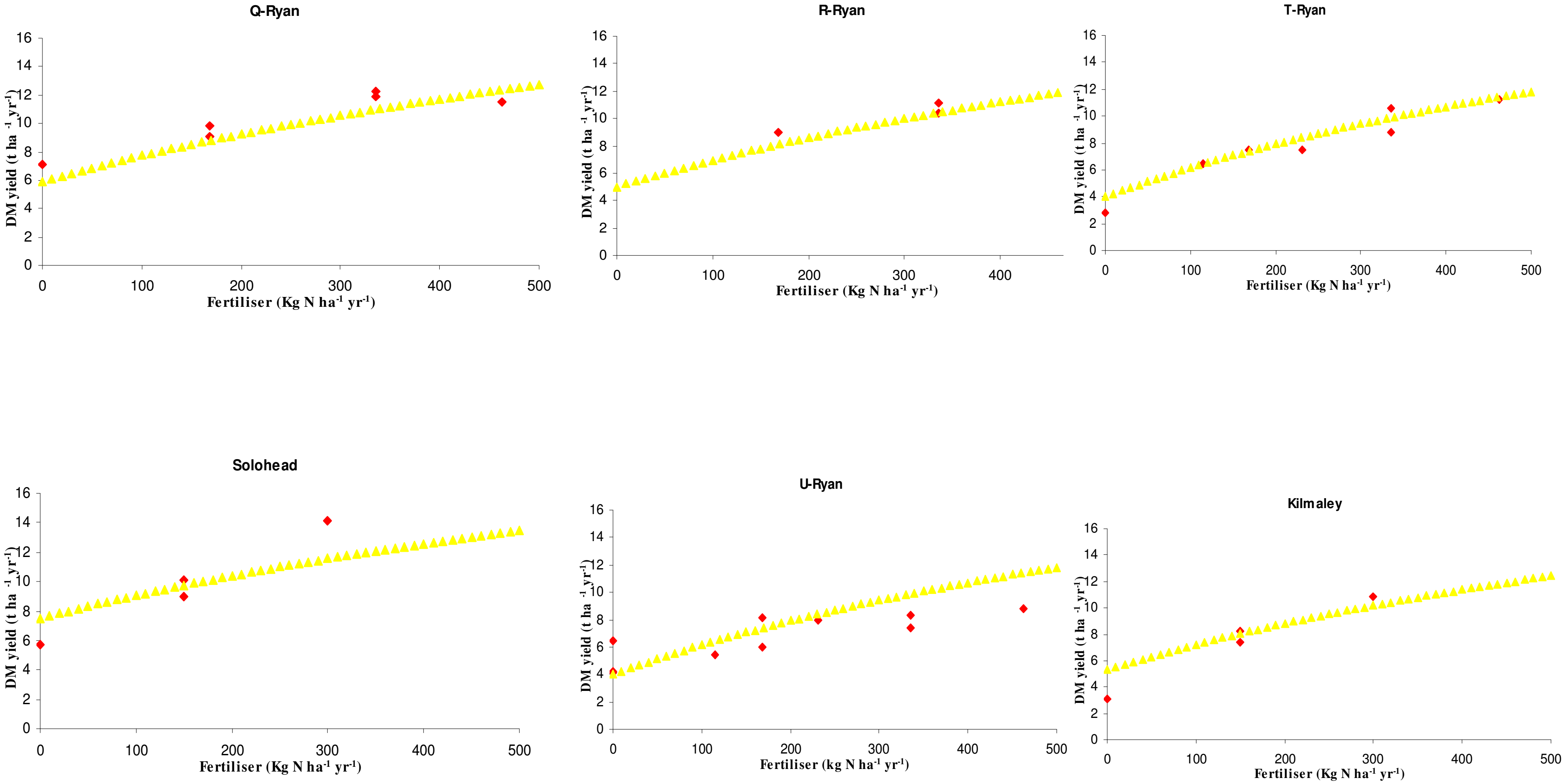


Figure 2.26. NCYCLE_IRL predictions and measured herbage dry matter yields (t ha^{-1}) for sites Q, R, T and U (Ryan 1974 ^{a,b}) and for Solohead and Kilmaley (K. O'Connell *pers .comm.)* in response to increases in fertiliser N inputs.

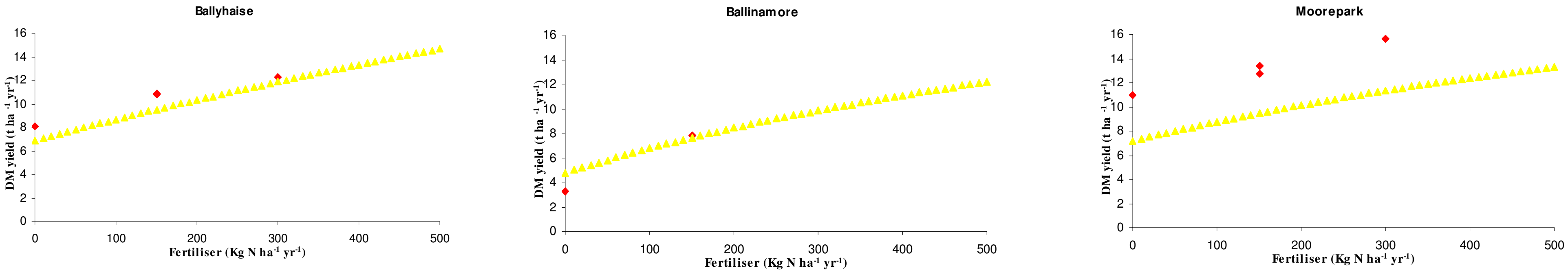


Figure 2.27. NCYCLE_IRL predictions and measured (K. O;Connell *pers comm.*) herbage dry matter yields (t ha^{-1}) in response to increases in fertiliser N inputs for Ballyhaise, Ballinamore and Moorepark

2.9.b Denitrification

Jordan (1989) reported annual denitrification N losses in the range 31 to 79 kg ha^{-1} from Northern Ireland swards on a poorly drained clayey soil receiving N fertiliser at a rate of 300 kg ha^{-1}. NCYCLE_IRL predicts annual denitirification N losses of 33 to 65 kg ha^{-1} which is within the range reported by Jordan (1989).

Denitrification rates from Ryan *et al.* (1998) were compared to simulated results from NCYCLE_IRL. The model predictions over-estimated the measured N losses by about 50 % for grazed grass on loam and sandy loam soils.

2.9.c Leaching

Ryan (1999) reported the N leaching losses over a two year period from a lysimeter with five soil types. NCYCLE_IRL predicted and measured N losses are shown in Table 3.5. Mineral N arising from manure applications was accounted for.

Table 2.5. NCYCLE_IRL predicted and measured annual N (kg ha^{-1}) losses from five soil types (Ryan, 1999).

	CAS$^{¥}$		**CLO$^{¥}$**		**ELT$^{¥}$**		**OAK$^{¥}$**		**RAT$^{¥}$**	
(kg N ha^{-1} yr^{-1})	**MEA***	**PRE***	**MEA***	**PRE***	**MEA***	**PRE***	**MEA***	**PRE***	**MEA***	**PRE***
Leached N	17-20	19.7	57-77	90	44-87	76	58-81	72.5	39-84	33

$^{¥}$CAS= Castlecomer (poorly drained clay loam deep soil), CLO = Clonroche (well drained loam-clay loam deep soil), ELT = Elton (well drained loam deep soil), OAK = Oakpark (well drained sandy loam shallow soil), RAT = Rathangan (poorly drained loam-clay loam deep soil).

*MEA= Measured range and PRE=Predicted value.

There is generally good agreement between predicted and observed annual N losses. However, NCYCLE_IRL appears to over-predict the observed N loss by about 25 % for one of the five soils (Clonroche).

In a recent study, Ryan *et al,* (2006) reported N leaching results, based on ceramic cups, for four grassland sub-managements (treatments) on an intensive Irish grassland dairy farm. The measured N leaching losses were much lower than those predicted by NCYCLE_IRL.

2.9.d Effect of soil type on N losses

NCYCLE_IRL predicts that the quantity of mineral N flowing in the system is greatly influenced by the texture and drainage class of the soil. Well-drained soils mineralise greater quantities of N partly due the enhanced aerobic soil conditions. Higher N losses in well drained soils compared with those from poorly drained soils would also be expected. The higher mineral N fluxes in well drained soils increases the supply of plant available N compared with the plant demand which may result in a surplus of N that becomes available for loss. This fact can be observed in Figure 2.28 a, b when total losses are compared. Within the 0-500 kg N ha^{-1} yr^{-1} fertiliser range, an average of about 20 % more total N losses are predicted to occur in the well drained soil (a) than in the poorly drained soil (b).

Texture and drainage class of the soil also influence soil water retention and thus, exert a large influence on soil anaerobiosis and solute transport. NCYCLE_IRL predicts that well drained sandy loam soil will lose most of the N surplus via NO_3 leaching while the poorly drained clay loam will lose more N through denitrification (Figure 2.28 a, b).

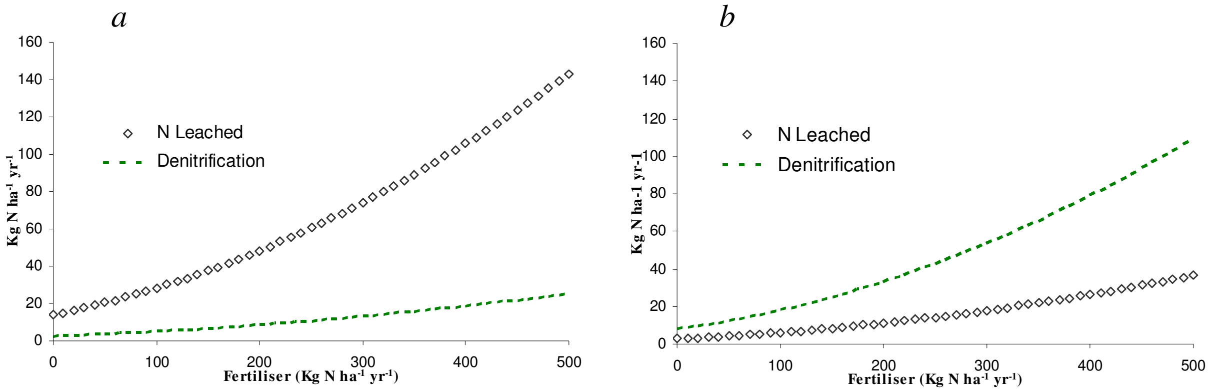


Figure 2.28. NCYCLE_IRL-predicted annual N leaching and denitrification losses (kg ha^{-1}) from a well drained sandy loam soil (a) and poorly drained clay loam soil (b).

3. NCYCLE_IRL AS A TOOL TO ANALYSE N LEACHING IN IRELAND

In order to study the status-quo of the dairy farming systems in Ireland, in terms of N leaching, the model NCYCLE_IRL was used to simulate two different types of managed grasslands in Ireland using N fertiliser input data from the fertiliser use survey in 2000 (Coulter *et al.,* 2002).

The study was divided into two subsections for different management of grasslands:
3.1 Dairy grazed grasslands
3.2 Grasslands for silage production

3.1 Dairy grazed grasslands

The annual fertiliser N inputs for grazed Irish grassland is determined by stocking rate (Coulter *et al.,* 2002). An average Irish dairy cow weighs 550 kg and is equivalent to 1 livestock unit (LU). Irish data indicates the annual N excretion of 1 LU is 85 kg. This data can be used to easily estimate the quantities of organic N associated with different SR and therefore different fertiliser N rates (Table 3.1).

In this exercise, NCYCLE_IRL was used to simulate grazed grasslands in Zone 6 with different SR and fertiliser N rates. Three different soil types were used to examine their effect on N leaching (Table 3.1). The annual hydrologically effective rainfall used was that for Cork which had a 10 year median value of 800 mm.

Texture and drainage status of the soil exert a big influence on the extent that N can be leached. The predicted average annual NO_3 concentration in the leachate increased as SR increased for all soil types (Table 3.1). The NO_3-N concentration for the soil types and drainage class ranged from 0.7 to 4.6 mg l^{-1} in poorly drained clay-loam soils, from 4.3 to 15.2 mg l^{-1} in moderately drained loam soils and from 5.8 to 22.1 mg l^{-1} in well drained sandy loam soils.

Table 3.1. Predicted values of annual N leaching (average NO_3-N concentration in the leachate) for different stocking rates (SR) and texture and drainage state in the soil in grazed fields located in the south of Ireland

S R	**organic N**	**Fertiliser N**	**No of farms**	**Leaching**		
LU ha^{-1}	kg N ha^{-1}	kg N ha^{-1}		**(average concentration) mg l^{-1}**		
				***SL-Good**	***L-Mod**	***CL-Poor**
<1.2	<102	58	41	5.8	4.3	0.7
1.2-1.5	102-128	101	55	7.7	5.6	1.1
1.5-1.9	128-162	137	128	9.5	6.8	1.5
1.9-2.25	162-191	182	153	11.8	8.4	2
2.25-2.6	191-221	248	89	15.7	10.9	3
2.6-2.9	221-247	297	31	18.7	13	3.8
>2.9	>247	348	16	22.1	15.2	4.6

* SL= Sandy Loam, L=Loam, CL= Clay loam and Mod=Moderate.

3.2 Grasslands for silage production

The fertiliser N-use for grass silage production was classified by region (Coulter *et al.,* 2002). NCYCLE_IRL was used to explore differences in N leaching between regions. The most common soil texture and drainage class and the net annual drainage volume in each region was assumed.

As might be expected the results of the analysis indicate considerable variability in herbage DM production (from 7.1 t ha^{-1}in the “border” and “west” region to10.4 t ha^{-1} in the “south” region. Farms in these three regions account for about 55 % of the farms surveyed and used by Coulter *et al.,* (2002). In general, farms in “border” and “west” areas have lower SR associated with more extensive grass-based enterprises (e.g. beef or sheep) while the farms in the “south” tend to have higher SR with more intensive enterprises (e.g. dairy).

Predictions of N leaching losses were higher in the regions with predominantly well drained soils and lower in those with predominantly poorly drained soils (Table 3.2). The levels predicted appear to comply with the Nitrate Directive’s maximum admissible concentration of 11.3 mg l^{-1} for water bodies when average NO_3-N concentration in the leachate was considered. It is acknowledged that the NCYCLE_IRL predicted concentrations refer to those below the root zone at field scale.

3.3. Practicality of the NCYCLE_IRL approach

Empirically-based, mass balance models have the advantages of producing an acceptably accurate prediction, based on relatively minimal input data, and are easy to use. In contrast, mechanistically-based models, which are often considered more scientifically robust, have large data demands (e.g. DNDC, Li et al. 1992) which in many instances will be difficult to fulfill, resulting in increased uncertainty in model output. Their scope is often fairly narrow because they were originally developed for specific goals and may not be applicable to the whole system of N cycling in grasslands. Currently, there is a trend towards more integrated modeling approaches, often using combinations of existing models e.g. STONE (Wolf et al. 2005), LANAS (Theobald et al. 2004) and MAGPIE (Lord and Anthony 2000). This enables complex problems to be addressed but exacerbates the difficulties of data availability, model run-time and the level of expertise required. The best models for assessing compliance with environmental constraints need to be transparent, simple and robust so that they may be applied and understood equally by those policing environmental constraints and those operating under them. Mass balance models, like NCYCLE_IRL, can fulfill this role.

Table 3.2. NCYCLE_IRL-predicted dry matter (DM) yield, annual leached N (load, average and peak concentration in the leachate) and denitrified N in grasslands for silage production for different Irish regions.

Region (AgCl[1] Zone)	**Fertiliser**	**farms**	**Soil type**	**DM**	**leached N**			**denitrified N**
				yield	**Load**	**Peak**	**average**	
	kg N ha^{-1}	**No**		**t ha^{-1}**	**kg ha^{-1}**	**mg l^{-1}**		**kg N ha^{-1}**
South-east (1)	136	138	*L-Mod	9.9	23.5	18	4.3	19.2
Dublin (3)	126	8	*L-Mod	9.5	16.7	16.5	5.6	17.2
Mid-east (2)	141	93	*CL-Poor	7.5	4.8	5.8	1.1	15.1
Midlands (3)	137	98	*SL-Good	9.6	32.5	33.6	6.5	5.7
Border (3)	116	172	*CL-Poor	7.1	4.1	5.5	0.8	12.8
South-West (6)	123	116	*CL-Poor	8.2	6.4	6.4	0.6	19.2
South (6)	151	219	*SL-Good	10.4	42.3	43.3	5.3	7.5
West (4)	102	167	*CL-Poor	7.1	4.2	5.5	0.6	12.7

* SL= Sandy Loam, L=Loam, CL= Clay loam and Mod=Moderate. [1] AgCl = Agroclimatic Zone (Figure 2.13)

This modeling exercise has made use of most of the current available data on N cycling in Irish pasture. While the construction of a highly mechanistic model may not have such a large data requirement, the use of such a model may be prohibited by the paucity of site-specific data available in the present case.

4. CONCLUSIONS

- Differences between the UK and Irish N fluxes in grasslands are mainly based on climatic conditions: in Ireland larger mineralised N pools are expected compared with the UK as the growing season is longer due to generally higher temperatures and rainfall rates.
- Gaps in the knowledge of Irish N fluxes in grasslands were identified as one of the main shortcomings to explain or further develop predictive tools such as NCYCLE_IRL: experiments which integrate measurements of N in herbage, denitrification, leaching and volatilisation will improve greatly the level of predictability in the future.
- Although variability in grass production in Ireland is still not thoroughly defined, some existing approaches were used in combination with experimental data to produce six agroclimatic zones. These zones were subsequently incorporated into a map within the NCYCLE_IRL interface.

- Soil type and drainage status, as found in NCYCLE, proved to exert a large influence on herbage productivity and the N flows in the grassland system. These differences were used to parameterise the mineralised N from previous years.
- A map of inputs of N from the atmosphere in different zones of Ireland was incorporated into the map interface of NCYCLE_IRL.
- New more accurate functions were developed for the animal sub-model in NCYCLE_IRL that partitions the ingested N between milk or meat production and excreted N and the subsequent partitioning of excreted N between dung and urine.
- A new NH_3 generator was developed to predict NH_3 volatilisation losses based on the average dietary N concentration. In addition, a function was added which allowed the user specify the proportion of N volatilised from urine and dung.
- The average NO_3-N concentrations in the leachate immediately below the rooting zone is derived in NCYCLE_IRL from the division of the leachable N load by the effective rainfall. Peak NO_3-N concentrations in groundwater and NO_3-N in the first 25 mm of drainage water are calculated using the relationships in NCYCLE.
- The proportion of leachable N that is actually leached was also incorporated into NCYCLE_IRL and was shown to be very sensitive to hydrologically effective rainfall, drainage and the type of soil.
- The interface of the original model was improved by coding NCYCLE_IRL in an object-oriented language (DELPHI 5). Some flexibility was built within the model in order to allow the user to explore possible deviations to the average conditions and to investigate the impact of changing the efficiency of some of the factors into the rest of the N fluxes.
- The NCYCLE empirical approach proved to be suitable to predict N fluxes from Irish grassland systems in most situations. However, the model predictions of leaching did not reconcile with some of those measured in lysimeter and field experiments. It is suggested that the observed leaching phenomenon in these experiments may be governed by non-average conditions or other parameters not accounted for in NCYCLE_IRL.
- NCYCLE_IRL proved to be a useful tool for analysing the N leaching response from grazed and cut grassland systems. It has potential to be used to assess, at farm level, the impact of legislative measures required under the EU Water Framework Directive.

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