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Principles of development of a mass balance N cycle model for temperate grasslands: an Irish case study

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Abstract

Because of current environmental legislation in European grass-based farming, there is a need to develop tools that can link nitrogen (N) production with losses to the environment. A mass balance empirical model (NCYCLE) is proposed to fulfil this role. This study describes the principles and stages to develop a mass balance N cycle model for Irish grasslands using the basis of the existing NCYCLE model. The model was reconstructed and validated using empirical data from herbage cutting experiments in different Irish conditions and new functions were incorporated to improve the predictions. Irish data on agroclimatic regions and atmospheric deposition were used to provide site specific calculations. Outputs from the model are presented and appear to agree reasonably well with measured data from Ireland.

Introduction

Temperate grassland agriculture is responsible for much of the world's production of meat and dairy produce. It occupies about 30% of the land area of Europe. Associated with productive grassland agriculture are serious environmental impacts that are now subject to legislative constraint. These include legislation on greenhouse gas emission (Kyoto protocol: Anon 1997), ammonia (Gothenburg protocol: UNECE 1999) and water quality (EU Nitrate Directive: Anon 1991). It is considered that in many European countries the most intensive grassland farmers will face difficulty complying with the EU Nitrate Directive as implemented through the management of nitrate vulnerable zones (NVZs). Methodologies are required to enable a quantitative linkage between the production arm of sustainability and N losses to the environment, in this case nitrate (NO_3^-) leaching for grassland farms located in NVZs, for both policy makers and farmers. Mathematical models offer this capability. In order to fulfil this role, models need to have qualities of robustness and be sufficiently simple to be used by the lay person while being sufficiently complex to embrace the full complement of soil, plant and animal processes involved in grassland N cycling.

The NCYCLE (Scholefield et al. 1991) modelling approach allows the complexity of the N cycle to be encompassed: NCYCLE is a mass balance empirical model that was developed in the UK for grassland and calculates the annual N transformations, fluxes and losses for cut and grazed grassland at the field scale, according to inputs specifying climatic zone, soil texture and drainage class, sward management and age and fertilizer 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 from ammonia (NH_3) volatilization and denitrification are also calculated and account for possible N pollution swapping to be identified.

NCYCLE model is different from other empirical approaches because it employs submodels that allow a high degree of application in relation to climate zone, soil conditions and land management so has the potential to be developed for many temperate grassland sites. In this paper we describe the general principles for reformulation of NCYCLE for application to N cycling in other temperate grasslands with specific reference to Ireland. The steps to construct the new model were as follows:

1. Identification of grassland agroclimatic areas.
2. Consideration of the case for the inclusion of a range of fertilizer types (e.g. urea or ammonium nitrate.
3. Development of a new mineralization submodel according to climatic zone and plant residue quality.
4. Addition of an Irish map in which different values of atmospheric N from deposition at field scale are associated to different areas of Ireland.
5. Modification of N uptake and partitioning in the plant.
6. Refinement of harvesting of herbage by cattle, N capture by the rumen and partitioning into product and excreta according to feed characteristics and animal type.
7. Simulation of partition of excreta into N in urine and dung according to feed characteristics.
8. Modified NH_3 production from urine and dung according to climatic zone and feed quality.
9. Derivation of the denitrification and leaching submodel according to climatic zone.

As a demonstration of the principles by which such a model can be developed we now present a case study of model reformulation for Irish grassland agriculture. Agriculture is an important area of economic activity in Ireland. Livestock and grass-based animal production enterprises account for almost 80% of gross agricultural outputs. Although traditionally the use of N in Ireland is generally low, there has been a dramatic increase in the use of fertilizer N since 1945: the most recent fertilizer survey (Coulter et al. 2002) showed that average use of N on grasslands was 136 kg N ha^{-1} $year^{-1}$ (48 and 176 kg N ha^{-1} $year^{-1}$ on beef and grazed dairy grassland, respectively and 95 and 151 kg N ha^{-1} $year^{-1}$ on beef and dairy grassland for silage, respectively). Beef and dairy production systems in Ireland have traditionally been based on grazed grass during the summer and feeding conserved grass during the winter. About 82% of all farms make silage, producing a total of 4.4 million tonnes of silage dry matter (DM) yield per year (O'Kiely et al. 1998).

As in many other countries in Europe, agricultural land is regarded as the main source of NO_3^- in most rivers and groundwaters (82% in Ireland, Environmental Protection Agency (EPA) 2002). Although the EPA (2002) concluded that water quality in Ireland was generally good in comparison with that in most European countries, it also identified eutrophication of inland fresh waters as 'probably Ireland's most serious environmental pollution problem'.

Average NO_3^- concentrations rarely exceed the EU legislated limits (11.3 mg NO_3^-–N l^{-1}) in Irish waters. Nevertheless, increasing levels of NO_3^- have been reported in the last few years. The new model, NCYCLE_IRL, provides a means by which NO_3^- peak and average concentration in drainage water may be predicted for different soil, climate and management scenarios.

Original NCYCLE and existing developments and applications

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. 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 (Figure 1) and cutting only system.

The input parameters are: soil texture, drainage status, land use history, age of sward, climatic

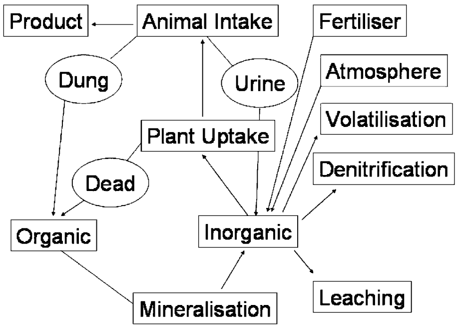

Figure 1. A flow diagram of the N transformations within NCYCLE (after Scholefield et al. 1991).

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 mineralized 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 volatilization (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 volatilized nor denitrified is accumulated in the leachable N pool.

Components of NCYCLE have been tested against independent data-sets (e.g. Scholefield and Blantern 1989) and the output from similar, empirically based models, such as GRASMOD (Van de Ven 1989). NCYCLE has also been used as a basis for calculating N balances on dairy farms (Jarvis 1993) and different modelling applications have been developed using the original NCYCLE approach as a basis for: (i) NO_3^- leaching from UK pig production systems (Worthington and Danks 1992), (ii) NO_3^- leaching at a catchment scale in the UK: NCATCH (Rodda et al. 1995; Scholefield et al. 1996) and MAGPIE (Lord and Anthony 2000), (iii) N fluxes in ley-arable rotations in the UK (Smith et al. 2001), (iv) a decision support system (DSS) to optimise fertilizer in order to meet environmental and economic optimum goals in the UK (Brown et al. 2005) and (v): a GIS framework for N leaching from terraced agricultural systems in Nepal (Collins et al. 1998).

Steps to the reformulation of NCYCLE into NCYCLE_IRL

The original NCYCLE was coded in PASCAL. NCYCLE_IRL was coded in DELPHI 5, an object oriented PASCAL-based programming language.

Development of grassland agroclimatic areas for Ireland

In order to asses the applicability of NCYCLE to Irish conditions, climatic variables from 30 year data-sets were used to compare weather patterns in Ireland with the corresponding ones in Great Britain. Monthly average temperature and rainfall in 6 stations in Ireland were graphed along with the corresponding values from 6 climatic regions in Great Britain. The patterns indicate that in general, the temperature and rainfall values in Ireland are within the range of values in the Great Britain. It was noted, though, that Irish locations tended to show higher temperature values in winter than the British sites (e.g., Figure 2). Therefore, small differences should be expected in processes that are highly dependent on temperature (mineralization, plant uptake, denitrification and indirectly, leaching). The growing and probably the grazing season in Ireland could be expected to be slightly longer than in Great Britain.

Variability of grass production across Ireland has not been studied in detail. However, the results derived from the experiments of Ryan (1974a, b, 1976) in different locations and soil types showed some variation if the same type of soils were compared in different locations. Some studies used the growing degree-days approach with little emphasis on grass production (Burke 1968; McEntee 1978), other studies such as Brereton (1995) used grass growth models that take the climatic variables (radiation, temperature and rainfall) into account and the most recent and

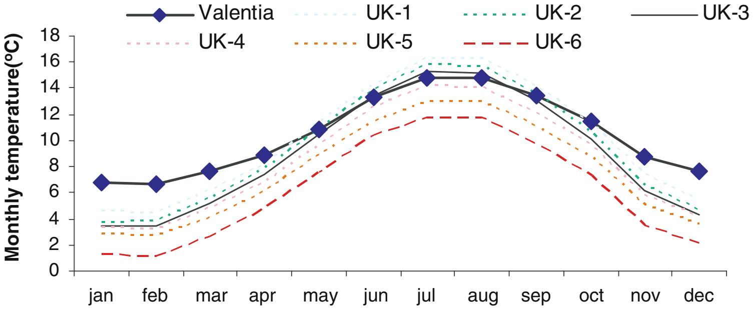

Figure 2. Comparison of monthly average temperature from a south west Irish location (Valentia) with temperature from 6 UK climatic regions.

complete study is that of Holden and Brereton (2004), who used hydro-thermal climate in conjunction with a statistical clustering technique to relate grass yield to climate data using crop simulation models.

In order to evaluate and quantify the differences in grass production among 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 the study of 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 differences in the annual fluxes of soil available N. Therefore, the main differences in N fluxes when comparing different agroclimatic regions are originated from different mineralized soil N. Annual mineralized N from the different soils and regions were derived from data obtained from the zero-fertilized plots of Ryan (1974a, b, 1976). By assuming that the total harvested herbage N yield would be 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:

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

As there were records of fraction of clover DM in the yields, the grass yield from N fixed from clover swards was estimated and subtracted from the total herbage yield assuming a N content in clover of 4% (Thomas 2004). Nitrogen released to the soil from dead plant material was also accounted for using a NCYCLE function that relates the N that has not been removed from the total N in the plant as herbage with the N concentration in the herbage.

Atmosphere-derived N was also estimated for different regions of Ireland by using the atmospheric-deposition map information of Jordan (1997). As a result, mineralized N from the soil was obtained from Equation 1.

When the effect of the soil type and drainage on rate of N mineralization was separated, the data of Ryan (1974a, b, 1976) resulted in a reasonably good agreement with yields measured in these agroclimatic zones: Ryan's data indicate that highest mineralization rates occurred in the zone 6 (South and south-west Munster), followed by zones 2, 1, 4 and 3 (Figure 3). Some of the Ulster area was not explored by Ryan's trials and therefore assumptions were made for zone 5 in order to cover the entire island (Figure 3).

Figure 3 shows the different mineralization adjustment factors for every zone. For instance, grasslands within zone 4 for a similar soil and history would have 77% of the N mineralized in zone 6.

The case for the inclusion of a range of fertilizer types

The impact of this major fertilizer source application on Irish grassland soils was investigated to

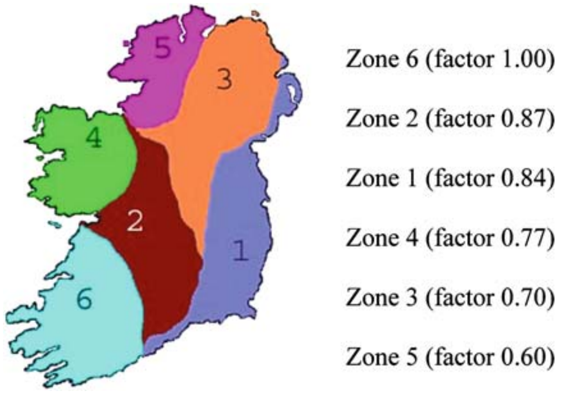

Figure 3. Agroclimatic regions in Ireland (after Holden and Brereton 2004).

assess the necessity of including urea fertilizer for simulation within NCYCLE_IRL. Neither the original NCYCLE (Scholefield et al. 1991) nor the trials of Ryan (1974a, b, 1976) were of use for this purpose as they are based on calcium amonium nitrate (CAN) fertilizer applications. Hence, literature on losses and herbage yields in Irish grasslands had to be reviewed: according to the last Irish fertilizer survey (Coulter et al. 2002), most of the surveyed farms used CAN for grazed grasslands (40%) and high N compounds (i.e. 23:2.5:5) for grasslands for silage production (49%). Nevertheless, urea plays a significant role in Ireland accounting for about 17% of N fertilizer used in both types of grasslands.

Some studies have investigated the efficiency of herbage production in Ireland using different fertilizer types and for different seasons: Murphy (1969) and Keane et al. (1974) found no difference between three different N sources (CAN, AN, urea) applied at same rate of N, either in total annual yields or yields in the first harvest. Herlihy (1980) concluded that only at mid-late season was grass production higher in grasslands fertilized with CAN than in those fertilized with urea. Stevens et al. (1989), in Northern Ireland, analyzed the effect of date of application and form of N on herbage production in spring: a range from -0.6 to 1.1 extra t DM ha^{-1} with urea use was found compared with CAN.

Evidence may suggest, therefore, that urea fertilization could result in some cases in slightly lower herbage yields and thus, probably greater and different forms of N lost. Nevertheless, the effect does not seem to be greater than a 10% difference (sometimes no difference). Application of urea in grasslands during the driest and hottest months of the year generally results in lower N fertilizer efficiency, which may be attributed to enhanced NH_3 volatilization under these conditions. Currently, the Irish code of best practice points out this fact and discourages farmers from using urea during late spring and summer (Humphreys et al. 2003).

Therefore, the inclusion of urea fertilizer as a factor to include in NCYCLE_IRL was ruled out because of the facts that: (i) urea has only, and not systematically, been found to result in lower herbage yields during late spring and summer and (ii) as the use of annual urea is not very high, the fertilizer survey does not indicate the seasonal usage of urea.

Development of a new mineralization submodel

Within NCYCLE, mineralization is considered to have two components:

(i) That derived from the mineralization of previous years' organic N pools influenced by the previous years' management.
(ii) That from mineralization of dead plant tissue from the current year's herbage growth and excreta (if grazed).

For NCYCLE_IRL, as noted in the previous section, this mineralization rate was derived from a multi-site trial involving 8–10 year old cut grass swards from long-term grasslands, a range of representative soil textures and a range of annual fertilizer N application including zero (Ryan 1974a, b, 1976). The mineralization starting values were derived from the total grass herbage N yield (prior to subtraction of clover N yield) of plots receiving no fertilizer N multiplied by a factor of 1.4 to allow for unharvested shoot and root material dying and mineralizing during the season. Nitrogen deposited from the atmosphere was also taken into account. It was assumed that the amount of dead plant tissue at the end of the year was equal to that at the beginning. Four soil types and 5 regions were considered, applying extrapolations where insufficient data were available. To moderate the values for a wider range of soil types, ages and locations, the same factors as in the

Table 1. Adjustment factors applied to the amount of N mineralized from soil organic matter on the basis of previous cropping history of the field and age of existing sward.

Previous land use	Age of sward (years)					
	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. Adjustment factors applied to the amount of N mineralized 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

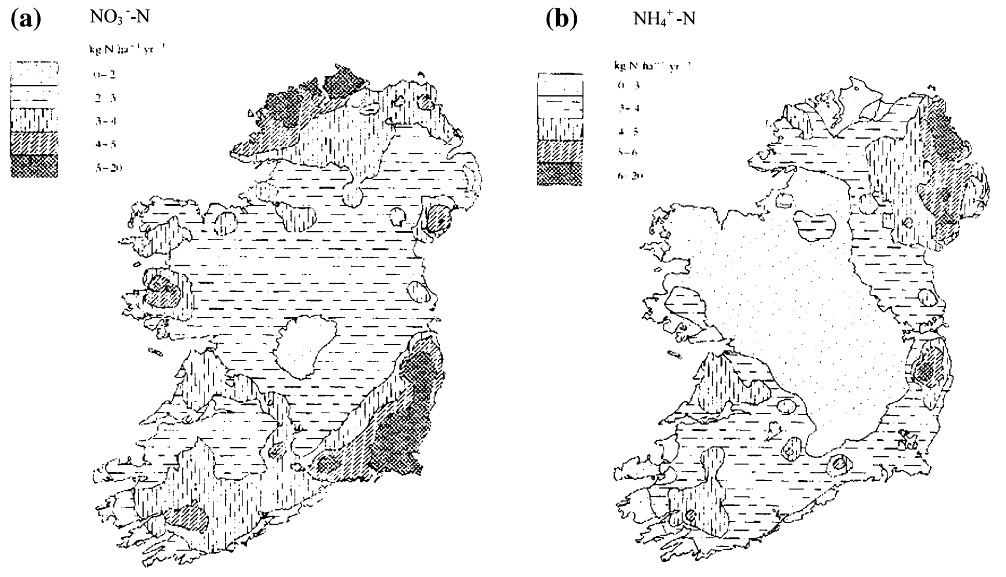

Figure 4. Maps of Ireland showing levels of deposition of (a) NO_3^-–N and (b) NH_4^+–N from the atmosphere (after Jordan 1997).

original NCYCLE were used (see Scholefield et al. 1991). The factors are as follows: 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 status of the soil (good, moderate and poor).

The factors in Table 1 indicate the fact that when grassland is cultivated and reseeded, there is a large increase in the mineralization of soil N in the first year (Young 1986) that is reflected in a higher yield (Culleton and McGilloway 1995). In Ireland, Culleton and McGilloway (1995) and Culleton et al. (1989) reported a DM yield gain of about 40% and 60%, respectively, during the first year after reseeding a long-term grassland.

The starting value for the mineralization of soil organic N calculations depended on the history class of the grassland (long term grassland: 280, mixed-ley arable: 105 and long-term arable: 42 kg N ha^{-1} year^{-1}) and this value was subsequently modified by applying multiplicative adjustment factors to account for the age of the sward, zone of the country (see Section 'Introduction'), soil texture and drainage status (Scholefield et al. 1991). The multiplicative values are shown in Tables 1 and 2 and Figure 3.

Addition of an Irish map in which different values of atmospheric N from deposition at field scale are associated to different areas of Ireland

The model uses the information on rainfall chemistry presented by Jordan (1997). Two maps showing the regional variation of NO_3^-–N and ammonium–N during the period of 1992–1994 were incorporated into the model (Figure 4). Nitrate deposition is shown to be <5 kg N ha^{-1} year^{-1} for most of Ireland. This value is only exceeded in

Wexford, part of South Wicklow and part of Donegal. Regarding NH_4^+ deposition, for most of the island the annual mean deposition is <6 kg N ha^{-1} year^{-1}, only being exceeded in North East Antrim and some small areas in Wicklow and Dublin counties.

Simulation of N uptake and partitioning in the plant

Using the same approach as the original NCYCLE, the N uptake by the plant competes with the processes of N loss for the mineral N pool in the soil. The proportion of plant uptake from the total inorganic N flux in the soil is calculated as a function of the total N flux in the soil. This relationship was found to be linear and negative, resulting in a higher proportion of mineral N flux being lost as gaseous and leaching losses with increasing amounts of mineral N in the soil (Scholefield et al. 1991).

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 mineralization. The difference between plant N and this dead tissue is herbage N. Different studies have estimated the N recovered by herbage and ranges between 45% (Ourry et al. 1988) and 77% (Hansson and Pettersson 1989) have been recorded. Although in the original NCYCLE, 62% (from Ball and Field 1987) was proposed as the default value, Ryan's cut herbage results (Ryan 1974a, b, 1976) suggested changing this value to 70% in Ireland. In any case, this value can be changed by the user in order to investigate the effect of changing this proportion (e.g. by changing grazing pressure) on N fluxes.

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

Studies from Ireland have shown different herbage responses to different N fertilizer applications, soil types, regions, cutting regimes, reseeding times and different sources of N applied, but very few (e.g. Ryan 1974a, b, 1976) include more than two of these factors as variables.

Simulation of harvesting of herbage by cattle, N capture by the rumen and partition into product and excreta

In the last decades, many changes have been made to ensure better efficiency of N use by animals by introducing new breeds and different diets. Incorporation of sensitivity to these changes would increase the accuracy of N predictions made by the NCYCLE model. Therefore, the approaches to the fate of ingested N used in the original NCYCLE were tested and compared with new approaches: Kebreab et al. (2001) analyzed the amount and form of N excreted under different dairy cattle production systems. To estimate the relationship between N intake and excretion, experiments containing similar diets that only differed in their level of proteins were studied. Mathematical representations of these relationships were obtained. Moorby (2003) reviewed literature on dairy cow dietary N efficiency and investigated the main reasons for inefficiencies in the use of dietary N leading to excretion products in the dairy cows.

Comparisons were made of simulated NCYCLE_IRL results obtained using the original NCYCLE functions and the functions proposed by Kebreab et al. (2001) using the data obtained from the review by Moorby (2003). The results are shown in Figure 5.

Results shown in Figure 5 indicate that both NCYCLE and NCYCLE_IRL would make predictions within the range of results reported by Moorby's literature review. On the other hand, NCYCLE tends to slightly over-predict N in urine and under-predict N in dung with most of the reviewed literature. The fact that the original NCYCLE uses functions that take into account the rate of protein: energy in the dairy cow feed intake (% N in the herbage) results in some poor predictions when trying to simulate intensive farms, which would normally be using different feed concentrates or supplements with a different protein: energy content.

As a possible way to overcome this shortcoming, the relationships proposed by Kebreab et al.

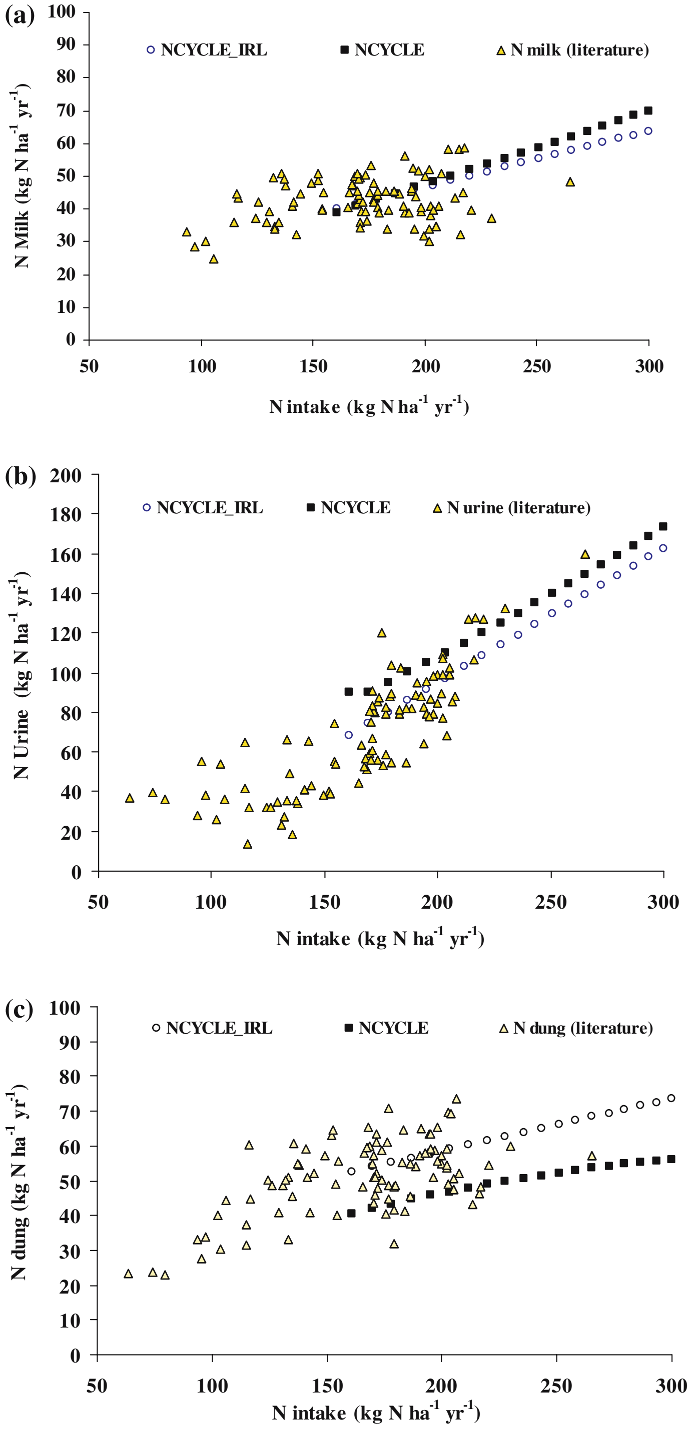

Figure 5. Comparison of NCYCLE_IRL °, NCYCLE ■ and literature Δ values of N in (a) milk, (b) urine and (c) dung over a range of N intakes (kg N ha^{-1} year^{-1}).

(2001) were adopted, which relate total N intake and amount and forms of excretion and averages the effect of the different protein: energy content diets during the grazing period. These new findings, therefore, suggest that the current dairy cow performance is best simulated by the Kebreab et al. (2001) approach and the total N in milk (kg N ha^{-1} $year^{-1}$) is calculated as follows:

$$N_{\text{dairy cow excreta}} = 0.17^{*}N_{\text{Animal Intake}} + 12.702 \quad (2)$$

$$N_{\text{dairy cow milk}} = 0.17^{*}N_{\text{Animal Intake}} - N_{\text{dairy cow excreta}} \quad (3)$$

The proportion of the N in the herbage that is transformed to beef animal product (liveweight gain) remained in NCYCLE_IRL as it was proposed by Scholefield et al. (1991). This proportion is related to the herbage N concentration according to a relationship derived from ARC (1980). The total N beef product (kg N ha^{-1} $year^{-1}$) is calculated as shown by the following equation:

$$N_{\text{beef product}} = N^{*}_{\text{Animal Intake}}((6.357 + 51.268^{*}0.47143^{\text{Percent N Diet}})^{*}0.01) \quad (4)$$

Steen and Laidlaw (1995), in Ireland, showed a liveweight gain per hectare of 20.5% and 22.5% when applying 360 kg N ha^{-1} $year^{-1}$ as opposed to 60 kg N ha^{-1} $year^{-1}$ in a low stocking rate and a high 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 fertilized with these two fertilizer rates.

Simulation of partition of excreta into N in urine and dung

Nitrogen excreted in faeces by dairy cows is reported to be rather constant in proportion to DM intake, about 0.6% of the dietary DM intake (Van Soest 1994). Urinary N excretion, on the other hand, appears to be more variable. Increases in dietary protein or N intake generally lead to substantial increases in urinary loss (Van Soest 1994) with almost all N ingested in excess of animal requirement excreted in urine (Peyraud et al. 1995).

In the original model, excreta from beef animals are calculated from the subtraction of N in beef product from the total N intake. The partitioning of excreted N between dung and urine reflects the concentration of N in the diet. It predicts that, with 1.5% N in the diet, 45% of the excreted N occurs in the urine whereas, with 4% N in the diet, 80% occurs in the urine (Scholefield et al. 1991). The fraction of excretion resulting as urine N was linearly related to the% N in the diet, represented by an equation as follows:

$$N_{\text{beef cow urine}} = 0.1369^{*}\%N_{\text{in the diet}} + 0.262 \quad (5)$$

Functions from Kebreab et al. (2001) were incorporated within the dairy cow urine and dung calculations: To estimate the relationship between N intake and excretion, Kebreab et al. (2001) conducted experiments in which similar diets that only differed in their level of proteins were fed to dairy cows. As a result, linear correlations were found for the relationship between excreted N and N intake. In NCYCLE_IRL the dairy cow excreta is calculated from the subtraction of N in milk from total N intake.

In the same study, N in dung (kg N ha^{-1} $year^{-1}$) was found to be linearly correlated with N intake and the equation was:

$$N_{\text{dairy cow dung}} = 0.15^{*}N_{\text{Animal Intake}} + 28.47 \quad (6)$$

Urine was then calculated from total N in the excreta minus the N in dung.

It is assumed that most of the urine N is mineralized within hours. It is also considered that 25% of the dung N is readily mineralizable and will contribute to the inorganic pool in the soil and to NH_3 volatilization.

Simulation of NH_3 production from urine and dung

Agriculture is considered to be the principal source of NH_3 emissions in Ireland. It accounted for 90% of the emission of 130 kt in 1998 (Humphreys et al. 2003).

Studies on NH_3 emissions from animal excreta were reviewed to investigate different approaches from that implemented in the original NCYCLE: In the original NCYCLE, the proportion of the urine N volatilized as gaseous NH_3 is considered to be 15%, this being the mean value of the results obtained using wind tunnels by Ryden et al. (1987), Vertregt and Rutgers (1987) and Lockyer and Whitehead (1990). This proportion can also be altered manually by the user in the model. The proportion of dung N volatilized was assumed to be 3% based on the results of MacDiarmid and Watkin (1972) and Ryden et al. (1987).

Different studies, though, have indicated broader ranges of volatilized NH_3 from: (a) urine, between 4 and 41% of the N (Ball and Ryden 1984; Lockyer and Whitehead 1990; Ryden et al. 1987; Vallis et al. 1982; Vertregt and Rutgers 1987; Whitehead and Raistrick 1993) with an extreme of 66% and (b) dung, ranged from 1 to 13% of the N (MacDiarmid and Watkin 1972; Ryden et al. 1987; Vertregt and Rutgers 1987; Sugimoto and Ball 1989). Therefore and in order to account for the variation of the proportion of N volatilized from the excreta, NCYCLE_IRL incorporated two relationships as an additional refinement to the existing sub-model from the original NCYCLE: the fraction of excreted N lost as NH_3 (Vfrac) was related to the average dietary N concentration (ND: g kg^{-1} DM) as follows:

$$\text{For dairy cows: Vfrac} = 2.717\,10^{-7} * \text{ND}^{3.389} (\text{Bussink 1996}) \tag{7}$$

$$\text{For beef cows: Vfrac} = 1.267\,10^{-4} * \text{ND}^{1.853} (\text{Jarvis et al. 1989}) \tag{8}$$

Production of the 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 (fertilizer, atmosphere, mineralization, urine, dung and dead plant material) and uptake by the plant component in the sward + NH_3 volatilization from urine and dung (Scholefield et al. 1991). The proportion of the remaining loss attributable to denitrification loss is then derived according to soil and drainage class from the matrix in Table 3, which is based on Scholefield et al. (1988). Leachable N is then obtained by difference.

Table 3. Proportion of N due to denitrification as a proportion of the loss due to denitrification and leaching, allocated on the basis of soil texture and drainage class.

Texture	Drainage		
	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

For NCYCLE_IRL, the same factors were used based on the fact that 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 influences the denitrification process rate by influencing the capacity of different kind of soils to retain water and thus altering the redox potential. Temperature also affects denitrification, many studies have suggested that Q_{10} is normally about 2 within 15–35 °C (Scholefield et al. 1997). Within the model temperature is accounted for when selecting different Irish agroclimatic zones. The temperature then influences the amount of N that flows in the soil and thus the amount of total N subject to denitrification or leaching losses.

As a change to the original NCYCLE proposed by Scholefield et al. (1991), NCYCLE_IRL was upgraded to produce actual N leached per hectare and peak and average N concentrations in the leachate using information from Scholefield et al. (1993, 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^-–N concentration on total leached soil NO_3^-–N were obtained for soils of different texture under grassland management. Average NO_3^- concentration was defined as the total amount of NO_3^- leached divided by the drainage volume.

Validation using field data

Herbage

When annual DM herbage yields from different field experiments (Ryan 1974a, b; O'Connell Pers.

comm.) were compared with those modelled using NCYCLE_IRL for a range of fertilizer rates (0–600 kg N ha^{-1} $year^{-1}$), a reasonably good agreement between modelled and measured values ($r^2 = 0.55$) was found (data not shown).

Table 4. Characteristics of the simulated field scenarios to compare predicted and measured herbage yields.

Site	Location	NCYCLE_IRL zone	Soil texture	Drainage
A[a]	Baltimore	6	loam	moderate
D[a]	Kilmeaden	1	loam	moderate
L[a]	Bunclody	1	clay loam	good
Q[a]	Tuam	4	sandy loam	good
R[a]	Tuam	4	sandy loam	moderate
T[a]	Ballinamore	3	clay loam	poor

[a]After Ryan (1974a,b, 1976).

Some of these scenarios on different soils and zones were selected (Table 4) and used to plot modelled and measured DM herbage yield values for a range of fertilizer rates (Figure 6).

On loam (sites A and D) and sandy loam (sites Q and R) soils, not only did NCYCLE_IRL predict herbage yields according to soil texture quite well, but it also succeeded in accounting for the effect of drainage and agroclimatic zone. For instance, a moderately drained loam soil in the agroclimatic zone 6 (site A) resulted in up to 13% more herbage DM yield than that in the agroclimatic site 1 (site D).

Herbage yield on clay loam soils tended to be well predicted with poor (site T) and moderate drainage (data not shown). However, herbage yield was over-predicted in well-drained soils (site L). This discrepancy could not be further checked

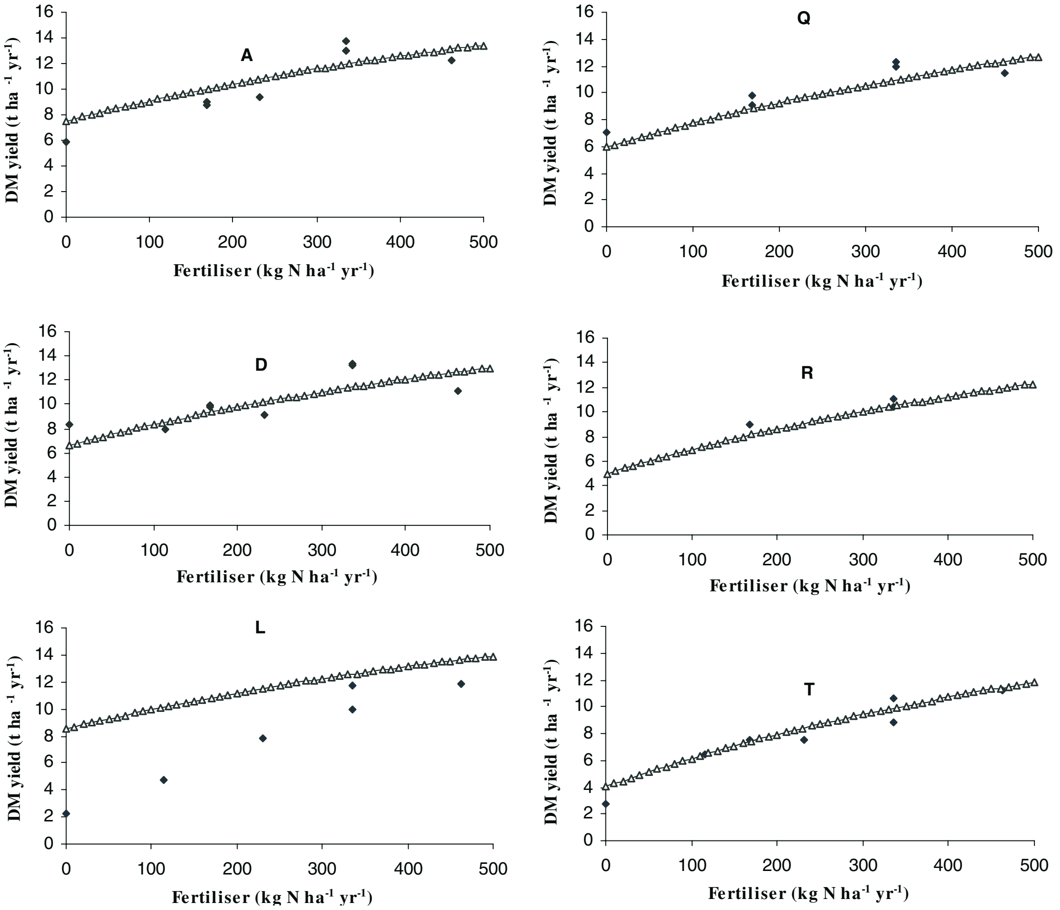

Figure 6. Predicted Δ and observed ◆ annual herbage values (t dry matter ha^{-1} $year^{-1}$) for a range of fertilizer rates in sites A, D, L, Q, R and T.

Table 5. Predicted and ranges of observed values in the 5 sites (after Ryan 1999).

SITE	CAS		CLO		ELT		OAK		RAT	
Leached N (kg N ha^{-1} $year^{-1}$)	M^a	P^a	M^a	P^a	M^a	P^a	M^a	P^a	M^a	P^a
	17–20	20	57–77	90	44–87	76	58–81	73	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).

[a]Measured (M) and predicted (P) results from Ryan (1999) and NCYCLE_IRL, respectively.

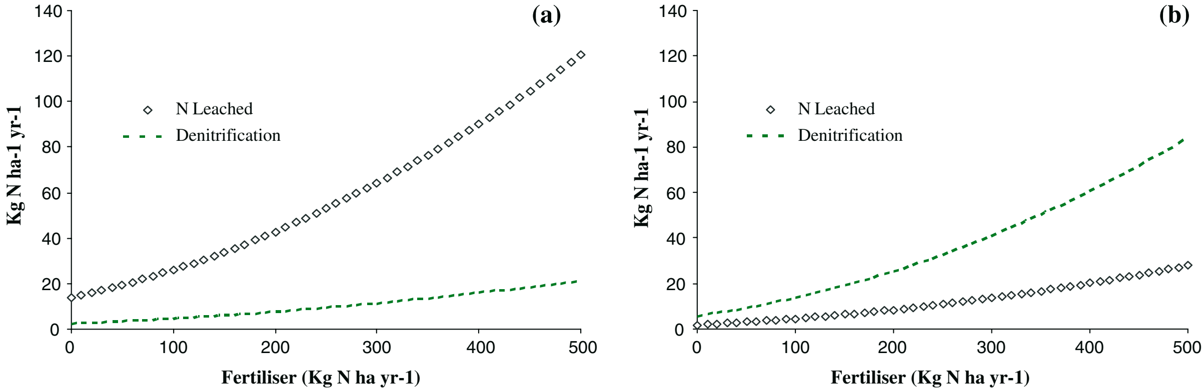

Figure 7. N leaching and denitrification losses from a well drained sandy loam soil (a) and poorly drained clay loam soil (b).

as we only had one site with this type of soil and drainage. Either an over-prediction of the mineralization rates from previous years or an incorrect assumption of the drainage class may have caused this discrepancy. The model simulates average weather conditions and therefore could not be expected to make good predictions of herbage from years of particularly good or bad growing conditions.

Denitrification

Jordan (1989), in studies carried out in Northern Ireland, obtained annual denitrification losses in the range of 31–79 kg N ha^{-1} $year^{-1}$ from swards on a poorly drained clayey soil receiving a rate of 300 kg N ha^{-1} $year^{-1}$ as mineral fertilizer. NCYCLE_IRL predicts in the range of 33–65 kg N ha^{-1} $year^{-1}$, which accords well within Jordan's range. However, denitrification rates from Ryan et al. (1998) were compared with simulated results from NCYCLE_IRL and the predictions resulted in an over prediction by NCYCLE_IRL of about 50% for grazed grass on loam and sandy loam soils.

Leaching

Ryan (1999) reported N leaching values for 5 sites and during 2 years. Measured (M) range and predicted (P) results are shown in Table 5. Account was taken of mineral N resulting from manure applications and annual net drainage was assumed to be over 500 mm.

There is generally a good agreement between predicted and observed values. In only one of the 5 soils (Clonroche) NCYCLE_IRL appears to over predict the N leaching by about 25%.

Model applications

Example of the effect of soil type on N losses

Figure 7 shows two examples of the effect of soil type on the form and quantity of N losses: NCYCLE_IRL predicts that the amount of mineral N flowing in the system is greatly influenced by the texture and drainage state of the soil. Well-drained soils mineralize greater amounts of N partly due the enhanced aerobic conditions of the soil. Higher N losses in well-drained soils compared with those from poorer drained soils would also be expected due to this greater mineral N flux and the reducing efficiency of N uptake by the plant when increasing the available soil N. This fact can be observed in Figure 7a, b when total losses are compared: within the 0–500 kg N ha^{-1} year^{-1} fertilizer 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 status of the soil also greatly influence the soil water retention thus exerting a large influence on soil anaerobiosis and solute transport. As expected, whereas the well-drained sandy loam soil is predicted to lose most of the N surplus via NO_3^- leaching, the poorly-drained clay loam loss is mainly via denitrification losses (Figure 7a, b).

NCYCLE_IRL as a tool to analyse N leaching in Ireland

In order to investigate 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 data from the survey of fertilizer use during 2000 (Coulter et al. 2002).

This study was divided into two subsections for different management of grasslands:

(i) Grazed dairy grasslands,
(ii) Grasslands for silage production,
(i) Grazed dairy grasslands.

According to the last survey of fertilizer use in Ireland (Coulter et al. 2002), Irish farms follow different fertilizer application rates (kg N ha^{-1} year^{-1}) for grazed grasslands according to different stocking rates (SR). Assuming that in Ireland a dairy cow of 550 kg equals 1 livestock unit (LU) and 1 LU produces about 85 kg N year^{-1} as excreta, the amount of organic N associated with different SR and therefore to different fertilizer rates can be easily estimated (Table 6).

In this exercise, NCYCLE_IRL was used to simulate grazed grasslands with different SR and fertilizer rates. As the survey of fertilizer use (Coulter et al. 2002) does not specify the sites of the farms, these farms were simulated to have the same location (South) and Annual Hydrologically Effective Rainfall (HER) was assumed to be that from Cork (median of last 10 years = 800 mm). Three different types of soils were used in order to see the effect of soil type on N leaching (Table 6).

According to our calculations based on the survey (Coulter et al. 2002), approximately 45% of the grazed dairy grasslands in Ireland exceed the amount of organic N (170 kg N ha^{-1} year^{-1}) proposed as a limit to be applied to the land in a National Action Plan area. Farms generally also own grasslands for silage production and hence, part of this organic N from the animal excreta would be generated when the animals are housed and spread to grasslands for conservation, making this percentage lower in reality.

Texture and drainage status of the soil exert a big influence on the extent to which N can be leached. When average concentration in the leachate is considered (Table 6), N leaching

Table 6. Predicted values of annual N leaching (average 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.

SR (LU ha^{-1})	Organic N (kg N ha^{-1})	Fertilizer N (kg N ha^{-1})	No of farms	Leaching (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.

increases as SR increases. Predicted values for different type of soils ranged: (i) 0.7–4.6 mg N l^{-1} in poorly drained clay-loam soils, (ii) 4.3–15.2 mg N l^{-1} in moderately drained loam soils and (iii) 5.8–22.1 mg N l^{-1} in well drained sandy loam soils. (ii) Grasslands for silage production: N fertilizer used for silage grasslands and classified by Irish region (Coulter et al. 2002) was used in order to explore the current differences in N leaching from farm fields located within different Irish regions. The most widespread texture, drainage status of the soil and net annual drainage volume were assumed for every region (Schulte Pers. comm.).

Results shown in Table 7 indicate that a great variability in the herbage production and N loss results can be expected for different locations. In terms of silage production, NCYCLE_IRL predicts a range of average DM yield of about 7 ('border' and 'west') to about 10.5 t ha^{-1} $year^{-1}$ ('south'). These 3 regions comprise about 55% of the total number of farms surveyed.

According to this survey (Coulter et al. 2002), whereas farms in 'border' and 'west' areas normally have farms with low SR, farms in the 'south' tend to be intensively managed. As expected risk of N leaching losses are high in the areas with predominantly well drained soils and low in the areas with predominantly poorly drained soils. When average concentration in the leachate is considered, all the farms appear to comply with the EU legislated limit even at the NCYCLE_IRL leaching scale (leached N below the root zone).

Practicality of the NCYCLE approach

Empirically-based, mass balance models have the advantages of producing an acceptably accurate prediction based on relatively few 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 fulfil, 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 modelling 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. We assert that mass balance models, like NCYCLE, best fulfil this role.

The development of the NCYCLE model for Ireland is presented as a case study and could be undertaken for any temperate grassland system. This kind of reformulation relies on good quality, integrated data over a number of years to encompass the range of weather patterns within

Table 7. Predicted annual values of N leaching (load, average and peak concentration in the leachate), dry matter (DM) yield and denitrified N in grasslands for silage production in different sites in Ireland.

Region	Fertilizer (kg N ha^{-1})	Farms No.	Soil type	DM (t ha^{-1})	Load (kg ha^{-1})	Leached N (mg l^{-1})		Denitrified N (kg N ha^{-1})
				Yield	Load	Peak	Average	
South-east	136	138	*L-Mod	9.9	23.5	18	4.3	19.2
Dublin	126	8	*L-Mod	9.5	16.7	16.5	5.6	17.2
Mid-east	141	93	*CL-Poor	7.5	4.8	5.8	1.1	15.1
Midlands	137	98	*SL-Good	9.6	32.5	33.6	6.5	5.7
Border	116	172	*CL-Poor	7.1	4.1	5.5	0.8	12.8
South-West	123	116	*CL-Poor	8.2	6.4	6.4	0.6	19.2
South	151	219	*SL-Good	10.4	42.3	43.3	5.3	7.5
West	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.

and between regions. This modelling 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.

Conclusions

NCYCLE_IRL represents one of the first efforts to integrate all the available data on N cycling in Irish grasslands. Modifications of the existing functions of the original NCYCLE (animal capture in the rumen, partition of excreta, NH_3 volatilization) and values for existing parameters (N from atmosphere, N from mineralization from previous years) improved the predictions from the original version. The applicability of the model was also enhanced by incorporating the peak and average N concentration in the leachate, which could be useful for investigating the implications to different environmental legislations such as the EU Nitrate Directive. 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 proved to agree well within the expected and measured ranges. Further extension of the applicability of the model should consist of more studies, the up-scaling to a farm level and the introduction of a shorter time-step, possibly monthly.

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