NGAUGE: A decision support system to optimise N fertilisation of British grassland for economic and environmental goals


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Abstract

The poor efficiency with which nitrogen (N) is often used on grassland farms is well documented, as are the potential consequences of undesirable emissions of nitrogen. As fertiliser represents a major input of nitrogen to such systems, its improved management has good potential for increasing the efficiency of nitrogen use and enhancing environmental and economic performance. This paper describes the development, structure and potential application of a new decision support system for fertiliser management for British grassland. The underlying empirically-based model simulates monthly nitrogen flows within and between the main components of the livestock production system according to user inputs describing site conditions and farm management characteristics. The user-friendly decision support system (‘NGAUGE’) has a user interface that was produced in collaboration with livestock farmers to ensure availability of all required inputs. NGAUGE is an improvement on existing nitrogen fertiliser recommendation systems in that it relates production to environmental impact and is therefore potentially valuable to policy makers and researchers for identifying pollution mitigation strategies and blueprints for novel, more sustainable systems of livestock production. One possible application is the simulation of the phenomenon of pollution swapping, whereby, for example, the adoption of strategies for the reduction of nitrate leaching may exacerbate emissions of ammonia and nitrous oxide. Outputs of the decision support system include a field- and target-specific N fertiliser recommendation together with farm- and field-based N budgets, comprising amounts of N in both production and loss components of the system. Recommendations may be updated on a monthly basis to take account of deviations of weather conditions from the 30-year mean. The optimisation procedure within NGAUGE enables user-specified targets of herbage production, N loss or fertiliser use to be achieved while maximising efficiency of N use. Examples of model output for a typical grassland management scenario demonstrate the effect on model predictions of site and management properties such as soil texture, weather zone, grazing and manure applications. Depending on existing management and site characteristics, simulations with NGAUGE suggest that it is possible to reduce nitrate leaching by up to 46% (compared with a fertiliser distribution from existing fertiliser recommendations), and fertiliser by 33%, without sacrificing herbage yield. The greatest improvements in efficiency are possible on sandy-textured soils, with moderate N inputs.

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1. Introduction

Experimental evidence, collected over the last three decades, of nitrogen (N) emissions from grassland (Ryden, 1981, 1984; Scholefield et al., 1993) has demonstrated the inefficiency with which N is frequently used. The loss of N has both economic and environmental consequences. The N loss pathways of primary concern to society are nitrate leaching and emission of the gases nitrous oxide (N₂O) and ammonia (NH₃). The increase in nitrate concentration in water bodies in recent decades has been a cause of concern because of the perceived potential threat to human health and because of the ecological and aesthetic consequences of eutrophication. In the UK, agriculture is the main source of nitrate in most UK rivers and groundwaters (Powlson, 2000) and is estimated to account for 69% of the emission of N₂O (Salway et al., 2001), which contributes both to global warming and to the depletion of the stratospheric ozone layer. Ammonia emission and subsequent deposition may contribute to water and soil acidification (Van Breemen et al., 1982) and is one of the main sources of the increased N supply to natural areas that may cause eutrophication of terrestrial and aquatic ecosystems (Isermann, 1990).

It has been shown (Scholefield et al., 1991) that there is a strong linear relationship between total annual inorganic N input to a grassland system and percentage recovery of that N by plants, such that in systems of low N flux, a larger proportion of the total N is recovered by the plant than in systems of higher N flux. Agricultural systems can be manipulated to changed efficiency simply by increasing or decreasing N input. Additionally, efficiency of plant uptake of N changes seasonally with weather and soil conditions and with physiological traits of the plant. Nitrogen fertilisers are the major N input to a typical dairy farm in the UK, comprising as much as 74% of the total N input (Jarvis, 1993), and are the input to the grassland N cycle that is most easily managed. It appears that there is much potential, therefore, to manipulate the efficiency of the system by appropriate management of fertilisers. However, simply reducing the fertiliser N input moves the system along the established efficiency relationship, and although losses can be reduced, production is also compromised. The challenge lies in the development and implementation of a system which lies above this line, i.e. is genuinely of greater N efficiency for the same total flux of N. This will involve both temporal and quantitative adjustment to fertiliser patterns.

Fertiliser recommendations for N have been produced in a similar format for England and Wales since 1973. With the exception of the most recent edition, recommendations have given little or no consideration to the potential environmental impacts of N application and have been rather generalised in relation to site variables. In the current version (RB209, MAFF, 2000), there is more site-specificity, in terms of soil types (three classes), rainfall (three classes) and previous management and N use. Although the publication points out the importance of achieving the right balance between profitable agricultural production and environmental protection, it also states that ‘the primary aim of the recommendations is to maximise the economic return from the use of fertilisers’. Improvement of the current UK recommendation system to effect improvements in efficiency would necessitate a change in emphasis from production/economic targets to a system driven, to a greater degree, by limitation of the undesirable exports: nitrate lost to surface water and N₂O and NH₃ emitted to the atmosphere. The application of such an approach would be especially beneficial in areas of particular sensitivity such as Nitrate Vulnerable Zones (NVZs, implemented under the Nitrates Directive, 91/676/EC), where the nitrate concentration of water draining from farmland is a fundamental consideration in the selection of agricultural management. The improved recommendation would seek to strike a compromise between production and environmental impact since the farmer still needs to achieve an acceptable level of income.

The objective of the research presented in this paper was to produce a decision support system (DSS) which would enable the efficiency of N use in grassland fields to be improved, by calculating the optimal temporal distribution of N fertiliser for a given field. In order to achieve this aim, the NGAUGE DSS was developed, to provide field-specific monthly N fertiliser recommendations, which improve the efficiency with which N is used, for user-specified targets. This necessitated simulating flows of N on a site-specific basis, with sensitivity to climate, soil properties, sward management and on-going weather,
and the development of the means of determining the best distribution of fertiliser N through the year to improve the efficiency of N use.

2. Model development

An existing empirically-based model of N cycling in grassland soils, NCYCLE (Scholtefield et al., 1991), was taken as the basis for the new model and DSS. NCYCLE is an annual, empirical model, based on published multi-site grassland data sets and has, since its creation, been validated for many of its key components (Rodda et al., 1995). NCYCLE simulates N flows through the major processes of N transformation in the soil and therefore links the input, production and loss components of the system. Sensitivity to soil properties, sward management and weather already exist within NCYCLE, although the latter is not sufficiently detailed for the purposes of the DSS development. NCYCLE is an annual model and therefore does not have the appropriate temporal resolution for prescribing fertiliser recommendations. The sub-models within NGAUGE therefore calculate N cycling through N components and processes on a monthly basis. In addition, there are five main areas in which NGAUGE extends the capabilities of the original NCYCLE model:

1. Inclusion of an optimisation procedure to identify a fertiliser amount and distribution according to criteria of herbage production and N losses to the environment.
2. Increased detail of average weather, and sensitivity to within-year on-going weather.
3. Simulation of losses of NH₃ from, and mineralisation of applied organic manures, and consideration of the magnitude and timing of this source of N in calculating fertiliser recommendations.
4. Provision of farm-gate N budgets (excluding import and export of animals).
5. More detailed simulation of nitrification and denitrification to enable prediction of N₂O emissions separately from dinitrogen (N₂) and nitric oxide (NO).

2.1. Model components

2.1.1. Plant uptake

At different times in the growing season, soil inorganic N is recovered by harvested herbage with contrasting efficiency. This was demonstrated in experiments such as those of Morrison et al. (1980) and Hopkins et al. (1990), in which equal amounts of fertiliser were applied in each time period (i.e. ‘month’), giving a range of annual amounts of N of, e.g. 0–750 kg N ha⁻¹ year⁻¹. Plots were cut on a 4-weekly basis and N in herbage determined. These multi-site trials provide a source of information on N recovery at different rates of fertiliser N and at sites with different soil types and land-use histories. Data from these experiments were used to derive a set of curves (Fig. 1), which describe the relationship between inorganic N flux (the sum of all the inputs to the soil) and plant N flux (including N in roots) for

![Fig. 1. Monthly N uptake (‘h’) factors used in the optimisation process.](image-url)
each month. Inorganic N includes N in fertiliser, N mineralised from soil organic matter and manures, N in urine (if grazed), N input from the atmosphere and ‘carried-over’ leachable N that was not leached in the previous month.

In order to calculate total N in plant from published data on N in herbage, assumptions were made about the $u$ factor (defined in Scholefield et al. (1991), as the proportion of N in the whole plant that is harvested by the animal or by cutting). There are few data to act as a guide to what the value of this factor may be. Parsons et al. (1983) report a value of 0.63 from measurements of carbon on continuously grazed pastures in south-west England, which is similar to the value of 0.62 assumed for the NCYCLE model (Scholefield et al., 1991). Hansson and Pettersson (1989), on perennial grassland, report values of 0.71 and 0.77, and Ourry et al. (1988) report values between 0.45 and 0.49. In order for the criterion of annual mass balance to be satisfied, internal consistency between mineralisation, plant N uptake and losses must be observed. By assuming a monthly distribution for mineralisation (see Section 2.1.3), the value of $u$ and plant N in each month can be fixed from the herbage data. Existing datasets and systems simulations of NCYCLE were used to quantify $u$ at a range of N input values. These data were then used to provide relationships between herbage N and $u$ for each month. The values of $u$ lie, for example, in a 300 kg N ha$^{-1}$ system between 0.2 (December) and 0.67 (June), with smaller values in winter months, when growth of the lamina region of the grass plant is limited, and large values in May and June, a time in which partitioning of N to the lamina and reproductive regions would be expected. From an N balance perspective, the lag between peak in herbage production (usually observed in May, particularly for cut systems) and mineralisation (frequently peaking in July or later) requires that a large proportion of the N taken up by the plant must be recovered in harvested material in the early summer months.

The N uptake curves define the efficiency of the plant in recovering N in each month and are analogous to the annual ‘$h$’ factor relationship used in NCYCLE. The comparison of these relationships between months is fundamental to the prediction of losses at each level of N input, and therefore to the operation of the optimisation procedure, described in Section 2.1.8.

The concentration of N in cut herbage was calculated using relationships between fertiliser N and %N in herbage, derived from Morrison et al. (1980). In the absence of better data for grazed herbage, the annual relationship used in NCYCLE was modified to produce a monthly relationship.

2.1.2. $N$ cycling through the grazing animal

The amount of herbage N ingested by the animal is determined by the $u$ factor for each month, as discussed earlier. The relationships used to calculate the partitioning of N within the animal into urine, dung and product were taken directly from Scholefield et al. (1991), and were based on empirical relationships describing the influence of herbage %N on N partitioning. As with NCYCLE, it was considered that most of the urine N is mineralised within a few days, and therefore enters the inorganic N pool within the month of excretion. Twenty-two percent of the N in dung mineralises in each month (i.e. passes into the soil inorganic N pool), as discussed in Scholefield et al. (1991).

2.1.3. Mineralisation

Mineralised N was considered to be derived from four components: (i) the previous land use; (ii) the herbage production in the current year; (iii) dung; and (iv) applied manures (Section 2.1.9). As in NCYCLE, the previous land use was categorised as long-term grassland, mixed ley and arable or long-term arable. Annual starting values for each of these were determined from the zero N fertiliser plots of cut-plot experiments of Morrison et al. (1980) and Hopkins et al. (1990), assuming no N loss and that, on an annual basis, 0.62 of the N in the whole plant is harvested by cutting (as NCYCLE). The starting values were 134, 76 and 27 kg N ha$^{-1}$ for long-term grassland, mixed ley–arable and long-term arable, respectively. These were then moderated by factors describing the effect of sward age, soil texture and drainage status. This annual total mineralised N was allocated to different months according to relationships describing the effect of soil moisture and temperature on mineralisation. For the former, it was assumed that mineralisation increases linearly between the soil’s permanent wilting point and field capacity. This is supported by the work of Stanford and Epstein (1974), who found the highest N
mineralisation between matric suctions of 0.3 and 0.1 bar (equivalent to 80–90% water-filled pore space), and that between this optimum range and 15 bar, there was a near linear relationship between mineralisation and soil water content. Reichman et al. (1986) report that ammonification and nitrification were almost directly proportional to soil moisture content at suctions of 0.2–15 bar. For the effect of temperature on mineralisation, a factor was calculated based on a linear increase of mineralisation rate with temperature, between a minimum (0) at 2 °C and a maximum (1) at 20 °C. Macduff and White (1985) and Blantern (1991) support a linear relationship between mineralisation and temperature between 2 and 20, and 4 and 13 °C, respectively. For each month, soil moisture content was calculated from soil moisture deficit (30-year average data for each zone and each month; see Section 2.1.10), using algorithms supplied by the National Soil Resources Institute, which assume for each of the five textural classes an effective depth of operation of the deficit, moisture content at field capacity and permanent wilting point, porosity and bulk density (C. Brown, personal communication). Mineralisation from the current year’s residues was calculated using empirically-derived functions, which relate monthly plant N to observed or estimated mineralisation. These values were then modified by factors which account for the effect of soil texture, drainage status, sward age and weather zone (using relationships with temperature and moisture as described earlier).

2.1.4. Denitrification

Denitrification was modelled as a function of soil inorganic N, water-filled pore space (WFPS) and temperature. Water-filled pore space was related to monthly denitrification using a relationship derived from the controlled laboratory experiments of Scholfield et al. (1997). Denitrification rate was assumed to increase linearly with temperature from 2 to 20 °C. The relationship between temperature and denitrification rate has been found to be linear by Cho et al. (1979), between 2.7 and 20 °C, and by Blantern (1991) between 7 and 16 °C, although at higher temperatures (e.g. 15–35 °C), a Q10 of 2 (i.e. a doubling in reaction rate for an increased temperature of 10 °C) has been reported (Stanford et al., 1975). A rapid decrease in denitrification below 5 °C has been observed (Bailey and Beauchamp, 1973), but minimum temperatures for denitrification may vary widely (Aulakh et al., 1992). Initially, the annual denitrification totals of NCYCLE were used together with weighting factors for soil texture, drainage status, temperature zone and rainfall zone to predict denitrification in each month. In order that denitrification could be calculated dynamically during the optimisation process (i.e. without recourse to annual totals), relationships were derived from these meta-data to predict denitrification from inorganic N in each month, retaining sensitivity to climate using the temperature and WFPS weighting factors described earlier.

In a monthly time-step model, it is not possible to account for the effects of individual rainfall events, although it is widely recognised (Jarvis et al., 1991; Li et al., 1992) that the occurrence of rain events, and time since a rainfall event, may be major determining factors of denitrification rate, and that good relationships between denitrification rates and controlling variables may be obscured by the considerable temporal variation that occurs with denitrification.

2.1.5. N-oxides sub-models

2.1.5.1. N₂ and N₂O from denitrification. This sub-model was conceptually based on the ‘hole-in-the-pipe’ model described by Firestone and Davidson (1989). This scheme postulates two levels of regulation for trace N-gas production: factors that control the rate of the overall process dictate the movement of N through the ‘process pipe’ (denitrification and nitrification processes); and factors that control the partitioning of the reacting N species to NO, N₂O or N₂ (i.e. control the size of the holes in the pipe through which the different N-gases ‘leak’).

In NGAUGE, N₂O and N₂ were assumed to be the only gaseous products of the denitrification process. Although NO has been proved to be produced during the microbial process of nitrification and denitrification (Firestone and Davidson, 1989), many studies have indicated that the NO gas does not constitute a major denitrification product (e.g. Anderson and Levine, 1986; Skiba et al., 1992; Neff et al., 1995; Parsons and Keller, 1995).

In order to predict N₂ and N₂O, the monthly values for denitrification were divided according to three factors: soil moisture content (WFPS), mineral N flux and mineralised N in the soil, using three functions to
represent the effect of these factors on the N2:N2O ratio as proposed by Parton et al. (1996). The level of nitrate was expressed as mineral N in order to be compatible with the main model.

Thus, the N2:N2O ratio was calculated as follows:

\[
N_2 : N_2O = \min \left( \left[ N\text{it} (\text{Min N}), N\text{it} (\text{Mineralis}) \right] \right) 
\times \text{Fr}(\text{WFPS}) 
\]

where Fr(WFPS) is the effect of soil WFPS on the ratio, Fr(Mineralis) is the effect of mineralisation rate on the ratio and Fr(Min N) is the effect of mineral N level in the soil on the ratio.

2.1.5.2. N2O and NO from nitrification. The monthly nitrification rate within NGAUGE was developed on the basis that the main substrates to be nitrified would be originated from the pools of ammonium (\(\text{NH}_4^+\)) mineralised from the organic matter (including excreta) and \(\text{NH}_4^+\) from the mineral fertiliser.

The zero-order kinetics approach described by Gilmour (1984) was implemented into the model with the nitrification rate constant being a function of temperature and soil moisture. The functions were as follows:

\[
\text{NIT rate} = K [\text{NH}_4^+]_i, \quad K : \text{month}^{-1} 
\]

\[
\text{NIT rate} = \left( K_{\text{maxW}} \times \frac{K}{K_{\text{max}}} \right) [\text{NH}_4^+]_i 
\]

where NIT rate is nitrification rate (kg N ha\(^{-1}\) month\(^{-1}\)), \([\text{NH}_4^+]_i\) is the level of \(\text{NH}_4^+\) in the soil at the beginning of the month and \(K/K_{\text{max}}\) and \(K_{\text{maxW}}\) are the soil temperature and moisture content factors, respectively, which affected the nitrification rate. The effect of temperature was modelled according to the Arrhenius equation.

\(K_{\text{maxW}}\) was derived from Macduff and White (1985), who used three different functions for soils under permanent wilting point, between permanent wilting point and field capacity and over field capacity.

From the predicted net nitrification pool, NO emissions were simulated on a monthly basis, following the approach of Davidson et al. (1993), in which NO fluxes are governed by the total amount of \(\text{NH}_4^+\)-N nitrified (nitrification), a factor describing the potential maximum percentage nitrified as NO (Max\%NIT) and a modifier accounting for the soil moisture (WFPS\(_i\)). The functions were as follows:

\[
\text{WFPS}_f = 0.0181 \times \text{WFPS} + 0.0165 
\]

\((\text{WFPS} < 55)\) (4)

\[
\text{WFPS}_f = -0.0667 \times \text{WFPS} + 4.6667 
\]

\((\text{WFPS} > 55)\) (5)

\[
\text{NO} (\text{g N-NO ha}^{-1} \text{month}^{-1}) = \text{Max\%NIT} \times \text{WFPS}_f \times \text{NIT rate} 
\]

Nitrous oxide emissions from nitrification were calculated in the model following the approach of Mosier et al. (1983) who designed a simple mechanistic model to predict daily N2O loss from soils from nitrification and denitrification. According to this study, the total amount of N2O emitted from the nitrification process (\(\text{N}_2\text{O}_{\text{nitr}}\)) is governed by the maximum potential rate of N2O from nitrification, assumed in NGAUGE to be 110 g N ha\(^{-1}\) day\(^{-1}\), based on maximum recorded field values (Yamulki, personal communication), a normalised (0–1) factor accounting for the amount of \(\text{NH}_4^+\) nitrified (En) and a soil moisture normalised (0–1) modifier (E\(\psi\)) as follows:

\[
\text{N}_2\text{O}_{\text{nitr}} (\text{g N ha}^{-1} \text{day}^{-1}) = 110 \times E\psi \times \text{En} 
\]

\(E\psi = 0.1 \quad \text{if} \quad \text{RWC (water content)} = [0–4]\) (8)

\[\text{Else} \quad E\psi = \left( \frac{3}{2} \times \text{RWC} - 5 \right) \times 0.1 \]

\[\text{En} = \frac{1}{1 + 1.335 \times e^{-1.24 \times \text{NIT rate}}} \]

where RWC is the soil relative water content, which is equal to the difference between measured soil water content and soil water content at wilting point divided by the difference between soil water content at field capacity and the soil water content at wilting point.

2.1.6. Nitrate leaching

Leachable nitrate, peak and average nitrate-N concentrations are presented by the model on an annual basis. For each month, soil inorganic N flux was calculated as the sum of atmospheric input, mineralisation of soil organic matter, mineralisation of dung and manures, fertiliser, urine and ‘leachable N’ carried over from the previous month. From this total, uptake of N by the plant, \(\text{NH}_3\) volatilisation and N lost by denitrification were subtracted. The fate of the remaining ‘leachable N’ depends on the month in question; for January, February and December, it was...
assumed that ‘leachable N’ contributes to the total annual leaching, and for other months it was passed to the succeeding month as a component of the inorganic N pool. In the growing season months, ‘leachable N’ is that which would be measured in the field as soil mineral N at the end of each month.

Peak and average concentrations of nitrate-N in leachate were calculated on an annual basis using the relationships derived by Rodda et al. (1995), which predict peak concentration from leached N, according to soil drainage and textural class (Fig. 2), and average concentration from leached N and drainage class.

2.1.7. Ammonia volatilisation

An NH3 emission factor of 1.6% was suggested for ammonium nitrate (Van der Weerden and Jarvis, 1997), which is the most widely-used fertiliser N form in Great Britain. This factor is currently used in the UK ammonia emission inventory (Misselbrook et al., 2000). It is generally the case that uniform emission factors are assumed across seasons (Pinder et al., 2004) and there are insufficient data available to determine different empirical relationships describing ammonia emission in different months. For NGAUGE, prediction of NH3 volatilisation from fertiliser and its sensitivity to weather was achieved using the model of Misselbrook et al. (2004). In this model, it is assumed that emission from ammonium nitrate fertiliser is moderated from a maximum value by temperature only. In NGAUGE, this gives emission factors ranging, for example, from 60% of applied N for dairy slurry with 10% dry matter, surface-applied in summer to 3% for dairy slurry with 2% dry matter, injected in winter.

2.1.8. Optimisation

The optimisation procedure is the means by which the best fertiliser distribution is calculated. There are two main concepts behind the operation of the optimisation procedure:

(i) Goal-seeking to a specified target.
(ii) Satisfaction of optimisation criteria.

The procedure was based on the set of monthly plant uptake (h factor) relationships, described earlier.

Initially, the average herbage N production of the farm is used as the target for the optimisation, but a field-specific target can be set by the user, and may be herbage N, N loss or fertiliser N. For one of these, the user selects the value desired (e.g. 300 kg herbage N ha\(^{-1}\), 50 kg N ha\(^{-1}\) loss, or 300 kg N ha\(^{-1}\) fertiliser applied). The end point of the optimisation is achieved when the model reaches the target value, satisfying the optimisation criteria (Fig. 3).
As the optimisation progresses towards its target, the optimisation criteria must be met in each iteration. The objective of the development of NGAUGE was to improve the efficiency with which N is used on grassland farms and the optimisation criteria were selected to reflect that. Three criteria are used, the one in operation in any given run is dependent on the target set by the user. All are a combination of maximising herbage and the efficiency ratio (ER), defined as kg N in herbage per kg N loss. These criteria may be combined in a number of ways that favour either one or the other, or treat them both almost equally, but their role in the running of the model may be considered as outlined in Fig. 3. While the optimisation criteria in run-time, and for the purposes of the ultimate end user, have been set, the procedure can be readily re-coded to enable other logical optimisation criteria to be met.

To begin the optimisation, an initial amount of fertiliser is allocated to all months and all pools are calculated (i.e. plant, herbage, product, mineralisation, denitrification, volatilisation, leaching, urine, dung). Fertiliser is provisionally transferred between all combinations of months, the pools are re-calculated and the values of variables required for the optimisation criteria (currently herbage and ER) are compared. The pair of months (i.e. one donating and one receiving fertiliser) with the best combination of herbage and ER is identified and the transfer of N is
effected. This new pattern of fertiliser is the ‘optimal’
distribution of fertiliser at this N level, but this
fertiliser amount may be insufficient to achieve the
specified target. If the target variable (e.g. herbage) 
has not yet met its target value, the procedure 
effectively returns to the top of Fig. 3 and another 
unit of fertiliser is applied to all months.

2.1.9. Manure management

In order for N pools to be calculated, account must 
be taken of N supply from application of organic 
manures. Two slurry types and two FYM types are 
available for selection in NGAUGE, each associated 
with default values of ammoniacal N, organic N and 
total N following selection of dry matter content by the 
user. Following application of manure (with amount 
and month of application specified by the user), 
volutilisation of NH₃ is simulated. The remaining 
inorganic N from slurry or FYM (ammoniacal 
N − volatilised N) is assumed to enter the soil 
inorganic N pool in the month of application. The 
mineralisation of organic N in manure (transfer of N 
between the manure organic N and soil inorganic N 
pool) is simulated each month according to appli-
cation date, C:N ratio (which is specified within the 
model according to manure type) and cumulative 
degree days above 5°C, according to the factors 
derived by Chadwick et al. (2000).

NGAUGE has not been designed to optimise 
manure application dates and amounts because it is 
considered that this will be determined by funda-
mental constraints of the system, such as volume of 
slurry storage available and by legislation. However, 
the N from manure is taken into account when 
calculating an optimal fertiliser recommendation.

2.1.10. Weather

Location (i.e. weather) has a substantial effect on 
both the initial calculations of N pools and the 
outcome of optimisation for a particular target. In the 
initial run of NGAUGE, the weather is assumed to be ‘average’ for that location (rain and temperature 
were obtained from seven weather stations represent-
ing the range of agricultural weather conditions in 
Britain (Penecuik, High Mowthorpe, Waddington, 
Wattisham, Shawbury and Yeovilton). Data used were 
monthly total rainfall, monthly average daily tem-
perature and soil moisture deficit, calculated for grass 
on a medium soil by the MORECS system (Thompson 
et al., 1981). These data were allocated to zones so that 
rainfall, temperature and atmospheric input may be 
considered independently, thus increasing the com-
plexity of the new model compared with NCYCLE. As 
with NCYCLE, there are three zones for atmospheric 
N input, setting values at 15, 25 and 35 kg N ha⁻¹ but 
in the new model there are six zones for rainfall (based 
on average summer rainfall) and six zones for 
temperature, giving a total of 36 possible tempera-
ture/rainfall combinations.

Weather impacts on plant growth both directly and 
indirectly, through:

(i) mineralisation (determining the supply of 
mineral N);
(ii) denitrification (influencing the amount of inor-
ganic N in soil);
(iii) plant growth directly.

The effects of soil water and temperature on mi-
neralisation and denitrification were described in S-
ection 2.1.3. For the effect of weather on plant growth, 
both temperature and soil moisture factors were con-
sidered. Plant N uptake was assumed to be limited by 
temperature according to a linear relationship between 
factors of 0 at 5°C and 1 at 20°C (as Dowle and 
Armstrong, 1990). The effect of water availability was 
cluded by assuming that the growth factor was 1 at 
the moisture content at 2 bar of suction for each soil 
texture and 0 at the corresponding moisture content at 
15 bar suction (permanent wilting point). Although 
water is considered available between suctions of 0-
.05–15 bar (Hall et al., 1977), that held at suctions of 
less than 2 bar is generally considered easily available 
(Brady, 1984). Similar limitation factor approaches to 
the calculation of the effect of moisture on plant gr-
owth have previously been adopted. Dowle and Ar-
rmstrong (1990), for example, assumed that maximum 
growth was possible between field capacity and wil-
ting point, declining linearly outside this range to 0 at 
100% soil moisture in the root zone and, at the op-
posite end of the range, at permanent wilting point.

2.1.10.1. Updating weather. Within an actual year of 
operation of the model, the observed N pools may be 
significantly affected by weather, and users may need
to change their fertiliser management in the light of incident weather in order to achieve their specified targets. NGAUGE has sensitivity to on-going monthly weather in order to achieve these objectives, which impacts on three major sub-models: denitrification, mineralisation and plant uptake.

Using the 30-year weather data described earlier, data were analysed for each rainfall and temperature zone, to produce five classes of data, representing the 10th, 30th, 50th, 70th and 90th centile. For the user, these centiles are accessed by the selection of weather categories for the preceding months (very wet, wet, average, dry and very dry for rainfall and very warm, warm, average, cold and very cold for temperature). These weather data, and denitrification and mineralisation factors derived from them are held in arrays and are used to re-calculate pools from the beginning of the year to the end of the last full month before today’s date. For example, for denitrification, arrays exist for temperature (of dimensions month, zone, centile) and water-filled pore space (of dimensions month, zone, centile, soil texture). To take an example of this, the 50th centile for a clay loam in zone 3 would give a water-filled pore space denitrification factor of 0.177, for the 10th centile this would be 0.02 and for the 90th centile 2.82.

Having re-calculated all pools according to the weather for the preceding months, the original recommendation (which was based on average weather) is updated to take account of the new weather information. This involves re-running the optimisation procedure. In this updating mode, although all months are included in the procedure and its calculations, movement of fertiliser can only take place between months that are forward of today’s date (including the current month). Clearly, there are often cases in which it may no longer be possible to reach the user-specified target, particularly where this is related to loss. Achievement of the target may now be associated with different losses, different herbage total or different fertiliser totals, and it is necessary that the user is aware of this.

3. Model validation

The performance of NGAUGE was evaluated in two ways: (a) assessment of the closeness of predictions and observations of N loss and transformation; and (b) investigation of the effect of NGAUGE fertiliser recommendations on N losses on paddocks of commercial dairy farms. Results of the latter will be presented in another paper. Data from a purpose-built cut-plot experiment in mid Devon, UK were used to evaluate the predictions of NGAUGE against field measurements. The site was on an old sward (more than 20 years old), which had received moderate fertiliser additions for the past 13 years. The average annual rainfall was 1025 mm, 550 mm of which was in excess of evapotranspiration. The plots (each 10 m × 3 m) were laid out in a randomised design with their long axes aligned with the direction of slope (approximately 5°) and were hydrologically isolated to a depth of 30 cm with vinyl sheet. Drainage via runoff and lateral flow was channelled to tipping bucket flow monitors with flow proportional samplers (Scholfield and Stone, 1995). Half of the plots were re-seeded in the year prior to measurements, to provide a contrast in sward age. Three N treatments were applied, corresponding to approximately 230, 300 and 420 kg N ha⁻¹ year⁻¹. Applications, as ammonium nitrate, were made monthly according to a pattern prescribed by the model. Mineralisation was determined on a monthly basis using the method of Hatch et al. (1990). Herbage was cut to 25 mm and weighed with a Haldrup forage harvester. Sub-samples were then dried in a forced draught oven at 85 °C for 18 h and weighed. Goodness of fit of observed and predicted fluxes was assessed using the method of Whitmore (1991).

Measured mean values of net mineralisation were generally greater than those predicted by the model in both years, although due to the large variation in observations on each treatment, observed and predicted rates were not significantly different in 9 out of 12 treatment years. Dry matter yields were generally under-predicted in year 2, and over-predicted in year 1, suggesting that there is no systematic error in the model’s predictions. Unusually low yields were observed in year 1 (e.g. less than 5 t ha⁻¹ year⁻¹ of dry matter from a fertiliser application of 350 kg N ha⁻¹ year⁻¹) on the old sward, and the reason for this was not clear. Nitrate leaching was generally well predicted by NGAUGE: in 8 out of 12 cases, there was no significant difference between modelled and measured values. The good agreement
between modelled and measured values is shown in Fig. 4 ($r^2 = 0.9$). It appears (Fig. 4) that NGAUGE may under-predict large values of leaching, but there are insufficient points at the high end of the range to determine whether this is genuinely the case. Peak nitrate concentration was also well predicted, with no significant difference between modelled and measured values in 8 out of 12 treatment years.

4. User interface description

NGAUGE was programmed in Borland Delphi 5. This is an object-oriented language, which associates portions of code with ‘events’ that happen to objects (e.g. a click on the ‘run’ button). It was written in a modular structure, using procedures and functions that can be called from any part of the program.

The user interface was designed and constructed in consultation with farmers, advisors, computer programmers and others with experience in DSS software development. User preferences suggested that a modular design with as few screens as possible should be aimed at. Thus, NGAUGE has two input and three output screens, each with logical positioning of check boxes, menus, edit boxes, tables and graphs. The first screen is used to enter generalised data about N use on the whole farm. From this, the model calculates the average N flows on the farm and provides a target herbage yield as an initial basis for fertiliser optimisation on individual fields (output screen 1). It also calculates an N balance for the whole farm. This was included in order to give farmers a general appreciation of the magnitude of N inputs and losses on their farms, and the potential for improvement with optimisation. In the current stage of the DSS, it is based on the generalised data entered about the farm as a whole on input screen 1, and does not make calculations based on individual field inputs. The second input screen is used to enter data about individual fields for which optimised fertiliser patterns are required. Output screen 2 displays optimised and non-optimised N budgets according to target, with a facility to graph these, a histogram of the optimised fertiliser distribution and a means to alter the optimisation target (e.g. Fig. 5). Output screen 3 is dedicated to updating the inputs and targets according to the weather experienced in each month in the year to date.

5. Use of NGAUGE for prediction of existing and optimised N flows on livestock farms

The degree to which optimisation is able to improve upon the predicted performance of a conventional system is dependent on the characteristics of the system (weather, soil type, fertiliser use, etc.) and the optimisation performed. Some examples of NGAUGE runs are given below to exemplify its
capability. For each scenario, the results from an optimised and non-optimised run are given. The conventional or non-optimised fertiliser distribution is based on MAFF (2000), for a fertiliser input of 300 kg N ha$^{-1}$.

### 5.1. Effect of soil texture

Soil texture exerts an important effect on N$_2$O, N$_2$ and NO losses by operating on both levels of regulation of N-gas products; it affects the process rate at which N is moving through the “pipe” (nitrification and denitrification net rates) and it controls the sizes of the holes through which the N-oxides “leak” (are transported to the atmosphere). In Table 1, non-optimised and optimised outputs are compared for a well-drained sandy loam and a poorly-drained clay loam soil, with the same management and climatic characteristics (11.5–12 °C and 400–450 mm average growing season temperature and rainfall, respectively). The effect of soil texture may be seen by comparing runs A and C, non-optimised runs for a sandy loam and clay loam, respectively. N$_2$O and N$_2$ fluxes in the clay loam soil were much higher than in the sandy loam soil, reflecting the better diffusion of the gaseous N compounds with lower water-filled pore space. The simulated N$_2$O:N$_2$ from denitrification and NO:N$_2$O ratios in the sandy loam were greater (by
factors of 2.6 and 64, respectively) than in the clay loam soil because of the enhanced water-filled pore space in the latter. Soil moisture governs whether nitrification or denitrification is the dominant process and strongly influences the corresponding turnover as well as the ratio of NO production over consumption rates. The slightly larger N₂O emission in optimised than non-optimised systems arises because the optimisation criteria are based on total N loss, rather than individual N loss processes. The effect is particularly apparent on well-drained soils, in which the largest component of loss is leached N.

For both soil textures, the efficiency with which the herbage yield was achieved (described by ER) was improved by optimisation. For grazed systems (Table 1), greater reductions in losses were possible following optimisation on the sandy loam (runs A and B) than clay loam (runs C and D) systems (35 and 17% reduction in loss for the sandy loam and clay loam, respectively). On heavier-textured soils, denitrification is often the major route of N loss, and the period with greatest potential for denitrification coincides with the period for greatest potential for grass growth. The fertiliser distribution for maximum plant uptake is thus always compromised by the criterion that ER must increase when fertiliser is moved between months in the optimisation procedure.

In these grazed systems with higher N inputs and N returns from the grazing animals continuing into September, the recommended fertiliser distribution for the sandy loam soil at both locations becomes more polarised towards the beginning of the year (see Fig. 6). The residual effects of these early applications will be carried through as soil mineral N into the later months. In the non-optimised system (run A), leached N from the sandy loam site accounted for 33% of the fertiliser applied. This percentage was reduced to 19% for optimised systems on the sandy loam soil (run B).

The fertiliser distribution from the optimisation was weighted more evenly through the growing season in the case of the clay loam soil, avoiding large applications in the period of maximum denitrification risk (March–May, Fig. 6). For the sandy loam soil, the denitrification risk is smaller because of the relatively smaller retention of water within the soil. Fertiliser distribution can also be a major factor affecting the proportion of N₂ over N₂O that it is actually emitted to the air. Comparing two sandy loam soils with the same

<table>
<thead>
<tr>
<th>Run</th>
<th>Soil type</th>
<th>Location</th>
<th>Management</th>
<th>Predicted N outputs from non-optimised and optimised grazed systems on soils of contrasting texture at location 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SL and WD</td>
<td>1</td>
<td>Grazed</td>
<td>Peak NO₃⁻N (mg L⁻¹)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N₂O</td>
</tr>
</tbody>
</table>
management characteristics in the same agroclimatic area but with a different fertiliser distribution (runs A and B). NGAUGE predicted that a more temporally even fertiliser distribution (run A) resulted in a lower N₂O:N₂ ratio (22% smaller). This result agrees well with other studies (Firestone and Davidson, 1989).

The optimisation process reduced the amount of fertiliser required to reach the herbage target by 9 and 18% for the grazed clay loam and sandy loam, respectively.

5.2. Effect of cutting/grazing management

The reduced efficiency of fields grazed by animals relative to cut-only fields can be seen for two contrasting soil textures in location 1 by comparison of runs A and C (grazed management, Table 1) with runs E and G (cut-only, Table 2). The ‘grazed’ scenarios simulate the effect of grazing with dairy cows from April to September, inclusive. The reduced ER of grazed areas, relative to cut systems (e.g. 2.8 for run A, compared to 5.9 for run E) is due to the greater total N in the system (as a result of animal excretion) and the addition of volatilised N to the total loss. Under the grazed system, all N losses (NO, N₂, N₂O, NH₃ and leaching) were greater than under cut systems, because of the greater total throughput of soil inorganic N. (To aid examination of the effects of grazing alone, this comparison does not address the potential applications of manure to cut fields, which may take place in reality. The effect of manure application is examined in Section 5.4.)

The ER for both cut and grazed systems was improved by optimisation, compared with the non-optimised runs, with the improvement under cut systems being greater than that under grazed. The smaller effect in grazed systems is due to the fact that a larger proportion of the N input, i.e. that from returns of dung and urine from grazing animals, cannot directly be optimised, although it is affected by the optimisation procedure.

5.3. Effect of weather zone

Selection of different temperature and rainfall zones has a significant effect on both the simulated fluxes of N and the fertiliser recommendation resulting from optimisation. To demonstrate this, two locations were compared: location 1 has an average growing season temperature of 11.5–12 °C (temperature zone 2) and an average growing season rainfall of 400–450 mm (rainfall zone 4), while location 2 has an average temperature of 9–10 °C (temperature zone 5) and a rainfall of 300–350 mm (rainfall zone 2). The sites were identical in all other respects. For an non-optimised cut system with 300 kg N ha⁻¹ fertiliser applied, the herbage dry matter yields from location 2 were 14 and 13% smaller for sandy loam (Table 3, run M) and clay loam (run O), respectively, than from location 1 (Table 2, runs E and G). Annual mineralisation calculated in a non-optimised run was 44 and 36% smaller at location 2 than location 1, for the sandy loam and clay loam soils, respectively. The cooler, drier location 2 also had smaller N losses.
### Table 2
Predicted N outputs from non-optimised and optimised cut-only systems on soils of contrasting texture at location 1

<table>
<thead>
<tr>
<th>Run</th>
<th>Soil type</th>
<th>Location</th>
<th>Management</th>
<th>Run</th>
<th>Outputs (kg N ha(^{-1}) year(^{-1}))</th>
<th>Peak NO(_3)-N (mg L(^{-1}))</th>
<th>ER (t ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Herbage Denitrification N(_2) N(_2)O N(_2)O NO</td>
<td>Nitrification Leached N NH(_3) Fertiliser</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>SL and WD</td>
<td>1</td>
<td>Cut</td>
<td>N</td>
<td>304 1.2 0.2 0.3 1.0 43.3 5.3 300 43.5</td>
<td>5.9 10.7</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>SL and WD</td>
<td>1</td>
<td>Cut</td>
<td>O</td>
<td>304 1.2 0.2 0.3 0.8 14.6 4.5 251 14.7</td>
<td>14.1 11.0</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>CL and PD</td>
<td>1</td>
<td>Cut</td>
<td>N</td>
<td>274 25.4 2.5 0.7 0.1 30.7 5.3 300 13.3</td>
<td>4.2 9.6</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CL and PD</td>
<td>1</td>
<td>Cut</td>
<td>O</td>
<td>274 16.7 2.8 0.6 0.1 6.2 5.2 286 2.7</td>
<td>8.7 9.9</td>
<td></td>
</tr>
</tbody>
</table>

SL = sandy loam; CL = clay loam; WD = well-drained; PD = poorly-drained; N = non-optimised; O = optimised; ER = efficiency ratio (kg N in herbage per kg N lost); DM = herbage dry matter yield.

### Table 3
Predicted N outputs from non-optimised and optimised systems with contrasting grazing management and soil texture at location 2

<table>
<thead>
<tr>
<th>Run</th>
<th>Soil type</th>
<th>Location</th>
<th>Management</th>
<th>Run</th>
<th>Outputs (kg N ha(^{-1}) year(^{-1}))</th>
<th>Peak NO(_3)-N (mg L(^{-1}))</th>
<th>ER (t ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Herbage Denitrification N(_2) N(_2)O N(_2)O NO</td>
<td>Nitrification Leached N NH(_3) Fertiliser</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>SL and WD</td>
<td>2</td>
<td>Grazed</td>
<td>N</td>
<td>350 1.1 0.3 0.5 0.5 63.2 34.6 300 63.5</td>
<td>3.5 9.1</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>SL and WD</td>
<td>2</td>
<td>Grazed</td>
<td>O</td>
<td>350 2.3 1.0 0.6 0.7 19.2 32.8 247 19.3</td>
<td>6.2 8.8</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>CL and PD</td>
<td>2</td>
<td>Grazed</td>
<td>N</td>
<td>301 26.4 3.2 0.7 0.1 43.7 30.1 300 18.9</td>
<td>2.9 8.0</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>CL and PD</td>
<td>2</td>
<td>Grazed</td>
<td>O</td>
<td>301 21.8 4.8 0.8 0.1 14.5 28.8 263 6.3</td>
<td>4.2 7.9</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>SL and WD</td>
<td>2</td>
<td>Cut</td>
<td>N</td>
<td>260 0.4 0.1 0.5 0.5 32.4 5.3 300 32.5</td>
<td>6.7 9.2</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>SL and WD</td>
<td>2</td>
<td>Cut</td>
<td>O</td>
<td>260 0.6 0.1 0.6 0.5 7.9 4.3 252 8.0</td>
<td>18.53 9.8</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>CL and PD</td>
<td>2</td>
<td>Cut</td>
<td>N</td>
<td>239 8.9 1.0 0.7 0.1 27.6 5.3 300 11.9</td>
<td>5.5 8.4</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>CL and PD</td>
<td>2</td>
<td>Cut</td>
<td>O</td>
<td>239 2.7 0.9 0.7 0.2 3.3 5.2 283 1.4</td>
<td>18.4 8.5</td>
<td></td>
</tr>
</tbody>
</table>

SL = sandy loam; CL = clay loam; WD = well-drained; PD = poorly-drained; N = non-optimised; O = optimised; ER = efficiency ratio (kg N in herbage per kg N lost); DM = herbage dry matter yield.
than location 1; denitrification was 65% smaller on clay loam soil at location 2 (run O) than location 1 (run G), for the non-optimised run.

Nitrous oxide and N2 fluxes in the warmer and drier area were generally higher than in the colder and wetter area, due in part to the increased mineralisation and greater inorganic N throughflow in the system. In drier areas, the N2O:N2 and NO:N2O ratios were generally higher than in wetter areas.

5.4. Accounting for manures

NGAUGE was used to investigate the effect of N from applied manures on N cycling in grassland systems and the degree to which fertiliser use may be reduced by taking account of this source. From a starting distribution of 300 kg N ha\(^{-1}\) fertiliser (based on RB209 as earlier) applied to a cut sward on a well-drained sandy loam soil (as run E), the application of 30 t ha\(^{-1}\) dairy slurry was simulated in February, May and November. This resulted in a significant increase in leached N (Table 4, run Q), which was particularly due to the November application. Fertiliser use was then optimised to achieve the same herbage yield with more efficient N use, resulting in a 15% reduction in fertiliser use (run R). The effect of optimisation on nitrate leaching is compromised in this run by the application of slurry, the timing and amount of which is not determined by the optimisation process but is considered as a fixed input. Injecting rather than surface spreading the slurry allowed a further 7 kg N ha\(^{-1}\) fertiliser to be saved (run T), and NH3 volatilisation to be substantially reduced (75%) demonstrating its effect as an NH3 abatement strategy. However, nitrate leaching was predicted to increase (37%) with this application method. NGAUGE predicted an increase of 17% in N\(_2\)O emissions when injecting slurry (run Q compared to run S, Table 4). This effect of larger N\(_2\)O loss from injected than surface spread slurry has been reported in the literature (e.g. Dosch and Gutser, 1996).

6. Discussion

The simulation of existing fertiliser, manure and grazing practices in the non-optimised mode of NGAUGE enables the user to investigate the likely
effects of changed management in any of these areas on both production and losses of N through the main processes of volatilisation, denitrification and leaching. The simulation of all of these processes also allows the potential effects of ‘pollution swapping’ to be monitored, as strategies for the abatement of individual loss processes are implemented. NGAUGE could, for example, be used to investigate the effect of the manure management changes associated with the recent NVZ guidelines on losses of N via both nitrate leaching, at which the legislation is aimed, and gaseous losses. This legislation affects both amount and timing of manure application to grassland of particular characteristics. The effect on production of the constraints imposed by this legislation could also be assessed, for individual fields and farms.

A second potential application of NGAUGE in non-optimised mode to investigate the effect of management is the simulation of extending the grazing season into periods in which the animals would traditionally be housed. This is an increasingly popular practice in the grassland areas of the UK with milder climate, such as the southwest of England and south Wales. The potential economic benefits of such grazing management have been demonstrated (Frame and Laidlaw, 2001), but debate continues about the potential environmental impacts of applying N, as fertiliser or grazing returns, outside the conventional grazing season. To assess the system fully, simulation would need to include the effects of the timing and amount of fertiliser application, the presence of grazing animals and the application of reduced amounts of animal manures during the traditional housed period. NGAUGE simulates the effects of all of these elements of the system and has usefully been applied to the assessment of extended grazing (Webb et al., 2005).

The facility to optimise fertiliser distribution within NGAUGE has a number of key advantages and applications. First, it allows N to be used more efficiently while still retaining the focus of the system on production targets. Secondly, and perhaps more importantly, it enables the focus to be shifted, and fertiliser plans to be developed for targets which reflect the changing, and multiple, objectives of modern agricultural systems. An example of this is the facility to use N loss, rather than production, as a target for optimisation. To make maximum use of this capability and to enable NGAUGE to contribute to an existing practical problem faced by the farming community, some changes to the operation of the DSS may be required, viz. making peak nitrate concentration rather than ‘N loss’ the target of optimisation.

The scope for improvement in efficiency through optimisation is limited by site factors, but more importantly by the level of N input to the system. The latter is obvious from the shape of the N response curve in plants: there is greatest scope for improvement with steepest gradient of the curve. At low N inputs, N response is dominated by mineralisation (largely unmanageable) while at high N inputs, response to incremental N input is very low.

While the model is capable of optimising the efficiency of N use for a particular grassland system, the optimised pattern of herbage production (high yields in early summer) may not be compatible with the farmer’s preferred stock management. UK livestock management encompasses a range of degrees of reliance on grazed grass, with some farms operating zero grazing systems with indoor feeding of cut and conserved forage, and others utilising grazed grass throughout the year. The distribution of herbage production predicted by optimisation would benefit more the former, which reflects the basis for the popularity of silage-based grassland production.

The NGAUGE DSS provides site-specific fertiliser recommendations for user-specified targets. In contrast to the existing UK fertiliser recommendation system (MAFF, 2000), the potential losses of N are taken into account in the production of this recommendation, both by ensuring that the target is achieved with the greatest ratio of herbage N to N lost, and by providing the facility for N losses to be entered as a target.

While there have been several other approaches to decision support for N fertiliser management, originating in The Netherlands (Dairy Farming Model, Van De Ven, 1996), France (AzoPât, Decau et al., 1997 and Delaby et al., 1997) and New Zealand (NLE, Di and Cameron, 2000; and OVERSEER, Wheeler et al., 2003), NGAUGE is unique in its combination of farmer-friendly user interface, sophisticated description of process and optimisation capability, that enables both production and environmental losses to be quantified. In addition, NGAUGE is capable of interfacing with budget- and indicator-based systems of fertiliser management (e.g. Jarvis et al., 1996; Schroder et al., 2003). Because of this combination of
ease of use and complexity of simulation, the DSS should be of benefit to a variety of users. In addition to its use by farmers and their advisors, it could be used by policy makers to explore mitigation options for enabling compliance with N loss legislation (e.g. for NVZ regulation compliance, as mentioned earlier); and by researchers to explore impacts of novel farm managements on pollution swapping and fundamental controls on the efficiency of the system. To aid progress towards these objectives the model could be further developed to enable a wider range of forage crops to be considered and to explore the advantages of within- and between-farm optimisation.

7. Conclusions

NGAUGE provides a basis for improved decision-making about fertiliser management on grassland farms. It is a tool which enables users to be more aware of the magnitude of N losses and provides a means of improving the efficiency with which N used on grassland fields. The potential for improvement in efficiency was found to be dependent on site characteristics and existing management, with the greatest improvement possible on sandy-textured soils with moderate N inputs. It was possible to reduce nitrate leaching by up to 46% and annual fertiliser use by up to 33%, without compromising herbage yield. Field-specific fertiliser recommendations are provided, according to the user-specified target, soil texture and drainage status, weather, land-use history and manure use. The optimisation procedure was developed with dual criteria of increased herbage production and reduced losses for a given N input, enabling increased emphasis to be placed on limitation of undesirable losses compared to existing recommendation systems. There is potential for manipulation of these criteria in future applications, to further shift the emphasis of the optimisation and resulting fertiliser recommendation, for example, where limitation of a specific loss pathway is of particular importance.

Acknowledgements

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References


