Author(s): C. RAHN, A. MEAD, A. DRAYCOTT, R. LILLYWHITE and T. SALO

Article Title: A sensitivity analysis of the prediction of the nitrogen fertilizer requirement of cauliflower crops using the HRI WELL_N computer model

Year of publication: 2001

Link to published version:
http://dx.doi.org/10.1017/S0021859601001174

Publisher statement: None

Journal of Agricultural Science, Cambridge (2001), **137**, 55–69. © 2001 *Cambridge University Press* 55
DOI: 10.1017/S0021859601001174 *Printed in the United Kingdom*

A sensitivity analysis of the prediction of the nitrogen fertilizer requirement of cauliflower crops using the HRI WELL_N computer model

C. RAHN[1]*, A. MEAD[2], A. DRAYCOTT[1], R. LILLYWHITE[1] AND T. SALO[3]

[1] *Department of Soil and Environment Sciences, Horticulture Research International, Wellesbourne, Warwick CV35 9EF, UK*
[2] *Biometrics Department, Horticulture Research International, Wellesbourne, Warwick, CV35 9EF, UK*
[3] *Department of Crops and Soil, Agricultural Research Centre of Finland, 31600 Jokionen, Finland*

(*Revised MS received 2 April 2001*)

SUMMARY

HRI WELL_N is an easy to use computer model, which has been used by farmers and growers since 1994 to predict crop nitrogen (N) requirements for a wide range of agricultural and horticultural crops.

A sensitivity analysis was carried out to investigate the model predictions of the N fertilizer requirement of cauliflower crops, and, at that rate, the yield achieved, yield response to the fertilizer applied, N uptake, NO_3-N leaching below 30 and 90 cm and mineral N at harvest. The sensitivity to four input factors – soil mineral N before planting, mineralization rate of soil organic matter, expected yield and duration of growth – was assessed. Values of these were chosen to cover ranges between 40% and 160% of values typical for field crops of cauliflowers grown in East Anglia. The assessments were made for three soils – sand, sandy loam and silt – and three rainfall scenarios – an average year and years with 144% or 56% of average rainfall during the growing season. The sensitivity of each output variable to each of the input factors (and interactions between them) was assessed using a unique 'sequential' analysis of variance approach developed as part of this research project.

The most significant factors affecting N fertilizer requirement across all soil types/rainfall amounts were soil mineral N before planting and expected yield. N requirement increased with increasing yield expectation, and decreased with increasing amounts of soil mineral N before planting. The responses to soil mineral N were much greater when higher yields were expected. Retention of N in the rooting zone was predicted to be poor on light soils in the wettest conditions suggesting that to maximize N use, plants needed to grow rapidly and have reasonable yield potential.

Assessment of the potential impacts of errors in the values of the input factors indicated that poor estimation of, in particular, yield expectation and soil mineral N before planting could lead to either yield loss or an increased level of potentially leachable soil mineral N at harvest.

The research demonstrates the benefits of using computer simulation models to quantify the main factors for which information is needed in order to provide robust N fertilizer recommendations.

INTRODUCTION

With around 750000 t of nitrogen (N) being applied to tilled crops in England and Wales, it is important to optimize its application. Excessive amounts of fertilizer N can reduce the quality and harvestability of crops, it can cause cereal crops to lodge, increase susceptibility to disease (Everaarts 1994), and reduce the storability of produce, as well as increasing the risk of nitrate leaching. Thus, in order to allow the environmental sustainability of both arable and horticultural crops, there is a great need to maximize the efficiency of N use and match it to N demand.

Many approaches for the estimation of fertilizer requirements are available. These include past experience, the application of the same amount of N to

* To whom all correspondence should be addressed. Email: Clive.rahn@hri.ac.uk

all fields, the use of simple tables, or calculations using measurements of soil mineral N. Decisions based on past experience, however, can be rather subjective and this approach may not always lead to sound decision making. There is always the temptation to apply additional N if early growth is poor, but the growth limiting factors may be poor soil structure, soil moisture, pest or disease problems rather than lack of N.

Systems based on a single fertilizer rate specific for each for all crops may produce satisfactory yields (Neeteson *et al.* 1987), but over-fertilization on some sites can give rise to nitrate leaching and increase the risk of variable produce quality. An improvement is to use simple tables, such as those provided in National fertilizer recommendations (MAFF 2000), which take account of previous cropping history, overwinter rainfall, and soil type to generate a 'soil nitrogen supply index'. However, in high residue situations, where large applications of manure have been applied (Shepherd 1993), or in intensive brassica rotations (Rahn *et al.* 1993, 1996*b*), timely measurements of soil mineral N allow more balanced fertilizer predictions to be made. Fertilizer recommendation systems, such as the 'KNS' system (Lorenz *et al.* 1989), provide a more comprehensive approach to fertilizer advice for field vegetable crops. They do, however, rely on the ability to record more than one measurement of soil mineral N during crop growth, in order to take account of the release of N from crop residues and loss of N by leaching. They also require that irrigation is available to support the late applications of N fertilizer. Another approach for field vegetables is provided by computer 'expert' systems, such as 'N Expert'. This system predicts the amounts of N available from crop residues and soil organic matter (Fink & Scharpf 1993), reducing the need for repeat measurements of soil mineral N.

Further improvement to the accuracy of the prediction of fertilizer requirements, however, requires an understanding of the effects of many interacting factors. Computer simulation models can be built to incorporate the effects of many factors – previous crop residues, the release rate of N from soil organic matter, soil type, crop demand, rooting depth, planting and harvest dates – and the interactions between them. Information on expected rainfall and temperature then allows such models to provide improved predictions of fertilizer requirements and hence optimize the use of available fertilizer inputs. One of the potential benefits of using good models to provide fertilizer recommendations is the provision of consistent and quantifiable advice. However, the usefulness of any model depends on the accuracy with which the input values can be measured or estimated.

The purpose of this paper is to briefly describe the WELL_N fertilizer prediction model, and to examine the sensitivity of its predictions for cauliflower crops with variability in a number of key inputs, including soil and meteorological factors. Cauliflowers are chosen as they have a large N requirement (up to 250 kg/ha) and because the penalties for failing to meet market criteria are so large that it is critical to predict fertilizer requirement accurately.

The results from this sensitivity analysis will identify those input variables on which the precision of any fertilizer recommendations is most dependent, and that have the greatest impact on yield and in reducing the risks of nitrate leaching.

MATERIALS AND METHODS

Model description and derivation

Over a number of years a dynamic simulation model for the prediction of N fertilizer requirements has been developed for a wide range of horticultural, and some arable crops. The research model upon which WELL_N is based has been described by Greenwood *et al.* (1996). The derivation and testing of the important functions in the model have been given in a series of papers – on growth rate and N concentration (Greenwood *et al.* 1986, 1990, 1991), root development (Greenwood *et al.* 1982), apparent fertilizer recovery (Greenwood *et al.* 1989) and

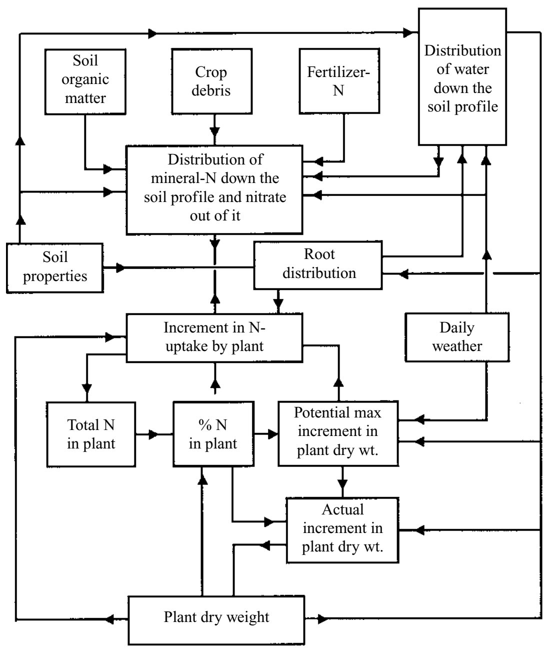

Fig. 1. The structure of the research model upon which WELL_N is based.

Table 1. *Required input data for WELL_N for this sensitivity analysis*

Information	Data	Derived from
Meteorological	Mean air temperature (°C), rainfall, and evaporation from open water (mm/day)	Weather data sets for 1982, 1990, 1992
Soil	Water content at field capacity (ml/ml)	0·20, 0·26, 0·38 for sand, sandy loam and silt loam soils respectively
	Barriers to rooting – depth (cm)	No limit to rooting depth
Crop residues	% N, dry wt t/ha, C:N and date of incorporation	No previous crop residue incorporated
Cauliflower crop	Time of planting (date)	April 15
	Weight at planting (kg/ha)	30 kg/ha
	% N at planting	Internal model calculation based on Greenwood *et al.* (1996)
	Duration of growth (days)	See Table 2
	Dry wt at harvest (t/ha)	See Table 2
Soil moisture deficit	Date (days), SMD (mm)	0 mm on 1 November
Soil mineral N	Layer size, number of layers, mineral N content in each layer	30 cm layer size, 3 layers; Mineral N distributed evenly to 90 cm depth on 1 April

leaching (Burns 1974). Versions of the whole model have been tested for potato (Neeteson *et al.* 1987), wheat (Greenwood *et al.* 1987), onion (Greenwood *et al.* 1992), and cabbage (Riley & Guttormsen 1993, 1994) and for a wide range of different arable and vegetable crops (Greenwood & Draycott 1989). The model has also been tested on a four-crop rotation containing cauliflower crops (Greenwood *et al.* 1996). The model has been 'commercially' tested by a number of farm consultants and growers (Burns *et al.* 1997).

WELL_N is currently available to run on IBM-compatible PCs and has been extended to include user-friendly input and output to encourage farmers, growers and their advisors to use it. The structure of the model is shown in Fig. 1, and calculations are performed on a daily time-step.

The inputs required for running the model are shown in Table 1. The model can provide recommendations for 25 crops. Having selected a crop, details of the intended fertilizer application method (top or base dressing) and the date of fertilizer application are required. The date of drilling or transplanting, duration of growth, and expected yield must also be provided. The assessment of prospective yield should be based on previous experience of marketable yields in the area. However, totally unrealistic yields will not be simulated if there is not enough N in the soil profile to support growth. Where data from previous crops are not available, suitable default values are used. Soil moisture deficit values are then required, the simplest approach being to use a value of zero at the date when drains begin to flow on non-cracking soils. A single measurement of soil mineral N, usually determined before planting, is required to initiate the model. This would normally be provided to at least 60 cm for cauliflower crops. Additional information, collected during crop growth, can be used to further improve crop management by checking the need for any top-dressings of N fertilizer. This might include details of rainfall, temperature, evaporation, irrigation, soil mineral N, soil moisture deficit, crop size and N content.

Outputs from the model include predictions of marketable fresh weight, total dry weight, the N content of the crop residues and the soil mineral N remaining at harvest, at a range of levels of applied fertilizer N. The recommended application level, taken as the level above which no increase in marketable yield is achieved, is highlighted, though in practice this optimum value is difficult to establish (Sutherland *et al.* 1986). Predicted values of the N content of crop residues and soil mineral N at harvest provide estimates of potentially leachable NO_3-N over the winter. The model also provides an estimate of leaching losses since the soil attained field capacity the previous autumn.

Design of simulation study

In designing a simulation study to characterize the uncertainty in input variables to the WELL_N model, a number of approaches are possible. Where there are a large number of input variables, a common approach

Table 2. *Key input variables, and the settings of these variables used in the sensitivity analysis*

Input factor	Factor levels
Soil type	Sand, sandy loam, silt loam
Rainfall	Low, average, high
Marketable yield (t/ha fresh weight)	20, 25, 30, **35**, 40, 45, 50
Duration of growth from 15 April (days)	56, 70, 84, **98**, 112, 126, 140
*Soil mineral N on 1 April (0–90 cm)	60, 90, 120, **150**, 180, 210, 240
Net mineralization rate (kg/ha/day @ 15·9 °C)	0·28, 0·42, 0·56, **0·7**, 0·84, 0·98, 1·12

Bold values are typical for crops in intensive horticultural rotations.
* Mineral N distributed evenly to 90 cm depth.

is to use Monte Carlo sampling to generate a distribution for the output variable(s) based on random samples drawn from the assumed distributions for the input variables. An improved coverage of the input variable space can be achieved by using Latin Hypercube Sampling (McKay *et al.* 1979), in which a stratified sample is taken for each input variable, ensuring that the achieved sample covers the full range of possible values for each input variable. Whilst these approaches should allow some assessment of the individual importance of each input variable, the independent assessment of both the main effects of input variables and the interactions between them can only be achieved by considering a set of factorial combinations for fixed levels of each input variable. The choice of whether to assess the complete set of factorial combinations or some fractional set depends on the number of input variables of interest, and the number of levels for each variable. To screen a large number of variables, only two or three levels of each factor might be considered, and with sufficient variables it is probably sensible to consider assessing a relatively small fraction of the complete factorial set.

For this study, prior knowledge of the model indicated that there were six key input variables (Table 2). An assessment of the importance of the main effects and interactions between these variables could be achieved by considering all factorial combinations of only two or three levels for each variable. However, a better impression of the shape of the response surfaces could be obtained by considering more levels for each variable, and the cost of assessing the increased number of combinations was small. Thus it was decided to consider all combinations of the four quantitative variables each at seven different levels, within each combination of three soil types and three rainfall levels (Table 2). A modified version of the WELL_N model was used in this study, allowing multiple runs of the model for all factorial combinations of the four quantitative variables.

Soil types were chosen to represent a range of soils with respect to the leaching of N: sandy, sandy loam and silt loam, which had water holding capacities at field capacity of 0·20 (leaky), 0·26 and 0·38 (retentive) ml/ml of soil respectively. The three meteorological data sets were selected from the 37 years available for Wellesbourne. One represented a year with an average level of spring and summer rainfall (1982 with 287 mm rainfall between April and September), and the second and third represented seasons with higher (1992 with 144% of the average) and lower rainfall (1990 with 56% of the average) respectively. The corresponding temperature data were used, with average temperatures of 11·96, 11·80 and 11·43 °C for the low, average and high rainfall data sets respectively. The central values of marketable yield, duration of growth, soil mineral N before planting, and mineralization rate (Table 2) were chosen to represent typical levels for field crops of cauliflower grown in East Anglia. A range of values representing between 40% and 160% of the central values were chosen covering expected variations in practice.

Other input data with fixed values included: the date when soil moisture deficit was set to 0 (1 November in the previous winter), and the cauliflower crops planting date (15 April). The land was taken to be fallow in the previous year. Soil mineral N was taken to have been measured on 1 April and the amounts shown in Table 2 were distributed uniformly to 90 cm.

For each combination of input factors, results were simulated at 15 different applied N fertilizer levels, ranging from 0 to 560 kg/ha in steps of 40 kg/ha. Predictions of marketable yield, N uptake, soil mineral N at harvest to both 30 and 90 cm depths, and leaching below both 30 and 90 cm, between planting date and harvest date, were made for each of the levels of applied fertilizer. The optimum applied fertilizer level was defined to be that producing 99% of the maximum yield. For each combination of the levels of the input variables, this value was estimated by inverse cubic interpolation (Johnson & Riess 1982; Genstat 5 Committee 1993) of the simulated yield values, thus avoiding the assumption of any particular parametric form of response curve. Appropriate values of the following variables were then estimated by cubic interpolation at this optimum applied fertilizer level:

(1) Achieved yield.
(2) N uptake by the crop.
(3) Soil mineral N at harvest to 30 cm and 90 cm.
(4) Nitrate-N leached below 30 cm and below 90 cm during growing season.

Table 3. *Summary of sequential analysis for applied fertilizer N to achieve 99% of maximum yield for average rainfall and sandy loam*

Treatment term	Treatment D.F.	Treatment SS	Treatment MS	Residual D.F.	Residual SS	Residual MS	Variance ratio	F-probability
Soil mineral N (S)	6	3489080	581513·3	2394	6528331	2627·0	213·246	< 0·001
Mineralization rate (M)	6	1228374	204729·0	2394	8789036	3671·3	55·765	< 0·001
Harvest yield (Y)	6	4331617	710936·1	2394	5685794	2375·0	303·971	< 0·001
Duration of growth (D)	6	608118	101353·0	2394	9409293	3930·4	25·787	< 0·001
Two-factor interactions								
S.M	36	2296	63·8	2352	5297660	2252·4	0·028	1·000
S.Y	36	215478	5985·5	2352	1981236	842·4	7·106	< 0·001
M.Y	36	4941	137·3	2352	4452478	1893·1	0·073	1·000
S.D	36	624	17·3	2352	5919588	2516·8	0·007	1·000
M.D	36	103936	2887·1	2352	8076982	3434·1	0·841	0·737
Y.D	36	18055	501·5	2352	5059621	2151·2	0·233	1·000
Three-factor interactions								
S.M.Y	216	981	5·4	2058	744643	361·8	0·013	1·000
S.M.D	216	1697	7·9	2058	4583284	22271·1	0·004	1·000
S.Y.D	216	906	4·2	2058	1353533	657·7	0·006	1·000
M.Y.D	216	1497	6·9	2058	3720872	1808·0	0·004	1·000
Four-factor interactions								
S.M.Y.D	1296	9810	7·6	0	0	*	*	*

* Indicates that no ratio could be calculated as the mean square for the denominator was zero.

The output variables were selected because they were of agronomic significance (achieved yield and applied N) or environmental significance (leached NO_3-N and soil mineral N at harvest (i.e. potential for leaching)), or linked these two aspects (N uptake).

Statistical methods

In order to identify the factors, and interactions between factors, to which the simulation model was most sensitive, the predicted responses within each soil type–weather combination were subjected to analysis of variance using Genstat 5 (Genstat 5 Committee 1993). As there was no underlying residual term with which to compare the effect of each main effect or interaction term, a sequential approach, based on the concept of stepwise regression (Sokal & Rohlf 1995), was developed. This approach identifies the more important effects, avoiding the spurious significance levels that would be indicated by using the more conventional approach of using high-order interactions as an estimate of error against which treatment effects are tested. The factorial structure of explanatory variables was maintained so that higher order interactions were only considered after all associated lower order terms. For each main effect, or interaction term, a variance ratio was constructed to compare the mean square due to the term with the variance due to unrelated terms (effectively the variability about the fitted term). So, for main effects the denominator of the variance ratio was the sum of the sums of squares for all other terms (main effects, two-, three- and four-factor interactions) divided by the sum of the degrees of freedom for these terms. The residual degrees of freedom for main effects are simply obtained by subtracting the main effect degrees of freedom (6) from the total degrees of freedom (2400) to get 2394. Similarly, for two-factor interactions, the denominator of the variance ratio was the sum of the sums of squares for all unrelated terms (the other two main effects, all other two-factor interactions and the three- and four-factor interactions) divided by the equivalent sum of degrees of freedom. Calculation of the residual degrees of freedom for each two-factor interaction involves subtracting both the interaction degrees of freedom (36) and the degrees of freedom for both associated main effects $(6+6)$ from the total degrees of freedom to get 2352. The denominator for variance ratios for three-factor interaction terms similarly excluded the variability due to the three associated main effects and three associated two-factor interactions. The residual degrees of freedom for each three-factor interaction is obtained by subtracting the interaction degrees of freedom (216), the degrees of freedom for each of the three associated two-factor interactions $(36+36+36)$, and the degrees of freedom for each of the associated main effects $(6+6+6)$ from the total degrees of freedom to get 2058. An example analysis summary is

Table 4. *Variance ratios for all main effects and statistically significant interactions – relevant degrees of freedom are given in Table 3*

Rainfall Soil type Treatment term	Low Sand	Low Sandy loam	Low Silt loam	Average Sand	Average Sandy loam	Average Silt loam	High Sand	High Sandy loam	High Silt loam
(*a*) N requirement to achieve 99 % of maximum yield									
Soil mineral N (S)	**211**	**209**	**209**	**213**	**213**	**214**	**189**	**194**	**200**
Mineralization rate (M)	**50·3**	**51·6**	**51·6**	**53·6**	**55·8**	**55·7**	**69·8**	**62·0**	**59·6**
Harvest yield (Y)	**308**	**304**	**304**	**311**	**304**	**303**	**314**	**328**	**321**
Duration of growth (D)	**31·8**	**31·9**	**31·8**	**26·7**	**25·8**	**25·5**	**21·8**	**20·8**	**22·6**
S.Y interaction	**3·04**	**6·85**	**6·96**	**6·06**	**7·11**	**7·31**	**6·34**	**7·96**	**7·79**
(*b*) Yield response (t/ha): difference in response for N fertilizer applied at recommended rate and zero applied N									
Soil mineral N (S)	**145**	**130**	**128**	**146**	**133**	**131**	**96·3**	**108**	**117**
Mineralization rate (M)	**47·6**	**54·2**	**57·0**	**51·3**	**58·7**	**62·1**	**55·6**	**64·6**	**67·7**
Harvest yield (Y)	**394**	**410**	**407**	**404**	**415**	**412**	**607**	**496**	**450**
Duration of growth (D)	**38·0**	**35·8**	**35·9**	**32·5**	**30·3**	**29·4**	**18·4**	**22·1**	**23·9**
S.Y interaction	**3·09**	**5·90**	**5·81**	**6·27**	**6·16**	**6·08**	**5·46**	**5·89**	**5·96**
M.Y interaction	1·06	1·21	1·23	1·18	1·31	1·33	**1·76**	**1·71**	**1·58**
(*c*) N leaching below 90 cm where N applied at recommended rate									
Soil mineral N (S)	*	*	*	*	*	*	**454**	**147**	**93·7**
Mineralization rate (M)	*	*	*	*	*	*	0·00	0·00	0·00
Harvest yield (Y)	*	*	*	*	*	*	**5·44**	**14·7**	**25·0**
Duration of growth (D)	*	*	*	*	*	*	**146**	**431**	**493**
S.D interaction	*	*	*	*	*	*	**17·8**	**41·6**	**34·0**
Y.D interaction	*	*	*	*	*	*	**13·4**	**13·5**	**18·9**
S.Y.D interaction	*	*	*	*	*	*	**16958**	**9311**	**37837**

Table 4. (*cont*.)

(*d*) N leaching below 30 cm where N applied at recommended rate									
Soil mineral N (S)	*	*	*	0·03	*	*	**4·81**	**6·51**	**4·41**
Mineralization rate (M)	*	*	*	0·65	*	*	**12·2**	**8·21**	0·87
Harvest yield (Y)	*	*	*	**7·76**	*	*	**16·3**	**17·51**	**3·98**
Duration of growth (D)	*	*	*	**1600**	*	*	**1351**	**1203**	**1849**
S.D interaction	*	*	*	0·09	*	*	0·47	0·23	**2·79**
M.D interaction	*	*	*	0·74	*	*	**3·32**	**2·29**	0·77
Y.D interaction	*	*	*	**1233**	*	*	**98·9**	**143**	**268**
(*e*) Mineral N at harvest 0–30 cm where N applied at recommended rate									
Soil mineral N (S)	0·03	0·11	0·14	0·03	0·11	0·15	0·01	0·03	0·14
Mineralization rate (M)	0·18	0·09	0·05	0·11	0·12	0·08	0·10	0·07	0·05
Harvest yield (Y)	**23306**	**33900**	**38932**	**18123**	**31364**	**32402**	**57703**	**75628**	**48834**
Duration of growth (D)	0·20	0·33	0·42	1·35	0·50	0·68	0·21	0·23	0·46
S.Y interaction	**1·82**	**5·36**	**8·32**	0·72	**5·46**	**7·33**	0·51	**3·19**	**8·53**
M.Y interaction	**5·85**	**4·41**	**3·04**	**2·76**	**5·20**	**3·32**	**7·56**	**7·63**	**3·49**
Y.D interaction	**7·23**	**23·9**	**38·4**	**88·4**	**34·3**	**59·0**	**179**	**54·1**	**58·8**
M.Y.D interaction	**1·83**	**1·67**	**1·33**	**2·54**	**2·03**	**1·83**	**3·67**	**4·94**	**1·84**
(*f*) Mineral N at harvest 0–90 cm where N applied at recommended rate									
Soil mineral N (S)	**118**	**117**	**117**	**118**	**115**	**115**	**97·2**	**113**	**116**
Mineralization rate (M)	0·42	0·52	0·54	0·44	0·54	0·89	0·52	0·72	0·72
Harvest yield (Y)	**853**	**848**	**846**	**845**	**853**	**849**	**1062**	**869**	**847**
Duration of growth (D)	0·08	0·09	0·10	0·15	0·13	0·14	0·37	0·15	0·13
S.Y interaction	**496**	**467**	**453**	**490**	**493**	**466**	**350**	**418**	**414**

* Indicates that no ratio could be calculated as the mean square for the denominator was zero. Ratios significant at the 0·1% level are shown in bold.

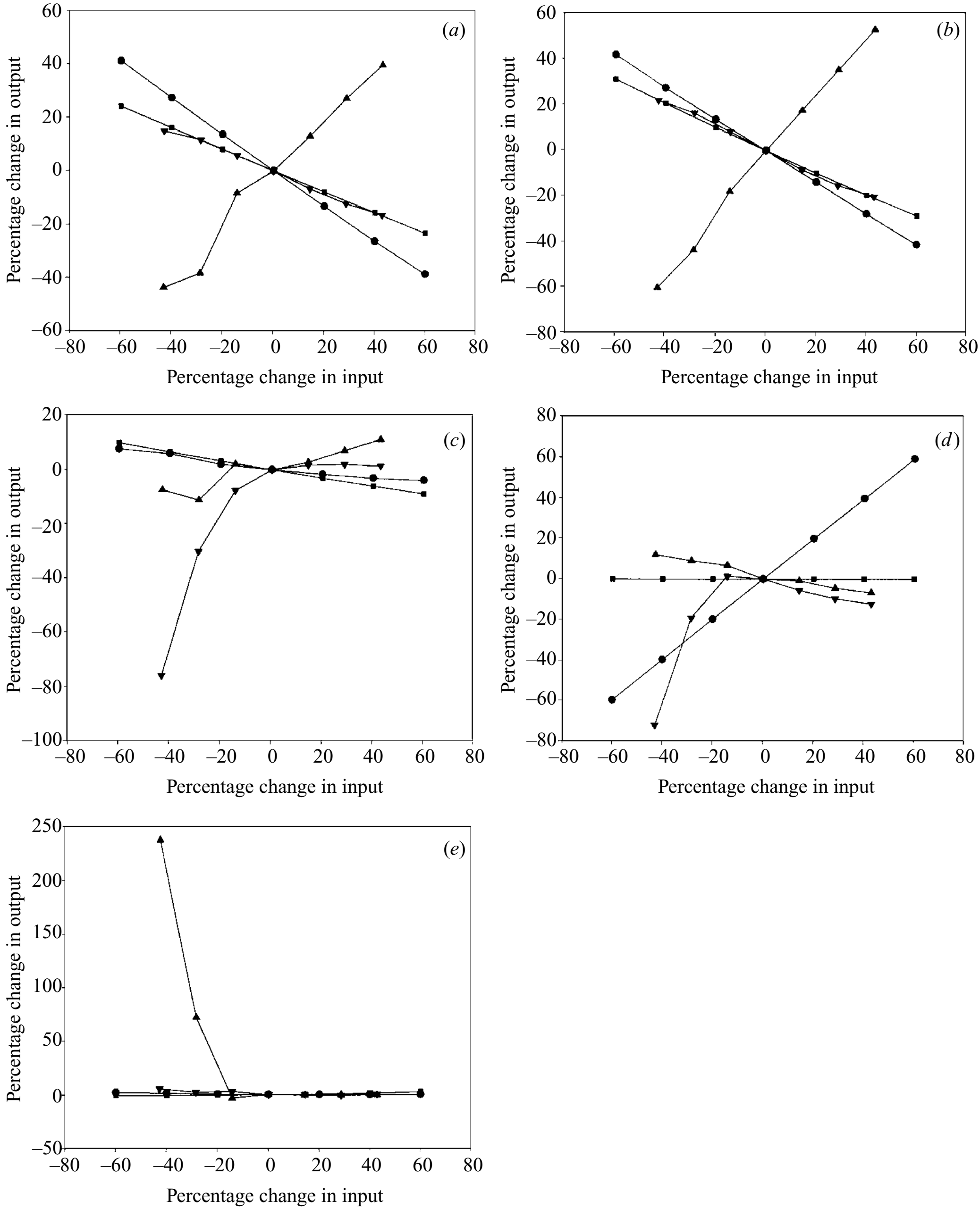

Fig. 2. Effects of variation in individual input factors on (*a*) applied nitrogen to achieve 99 % of maximum dry weight, for average rainfall on sandy loam soil, (*b*) increase in dry weight at optimum applied N relative to that at zero applied N, for average rainfall on sandy loam soil, (*c*) the amount of NO_3-N leached from 0–30 cm, for high rainfall on sandy soil, (*d*) the amount of NO_3-N leached from 0–90 cm, for high rainfall on sandy soil, and (*e*) soil mineral N in 0–30 cm at harvest, for average rainfall on sandy loam soil. Effects shown for soil mineral N (●), mineralization rate (■), yield expectation (▲) and crop duration (▼). Mid-point values are given in Appendix A.

shown in Table 3, also indicating the degrees of freedom associated with each variance ratio.

Where output variables were sensitive to variation in the input factors, example responses were shown graphically, either as response curves in 'spider' diagrams (for main effects) or as three-dimensional

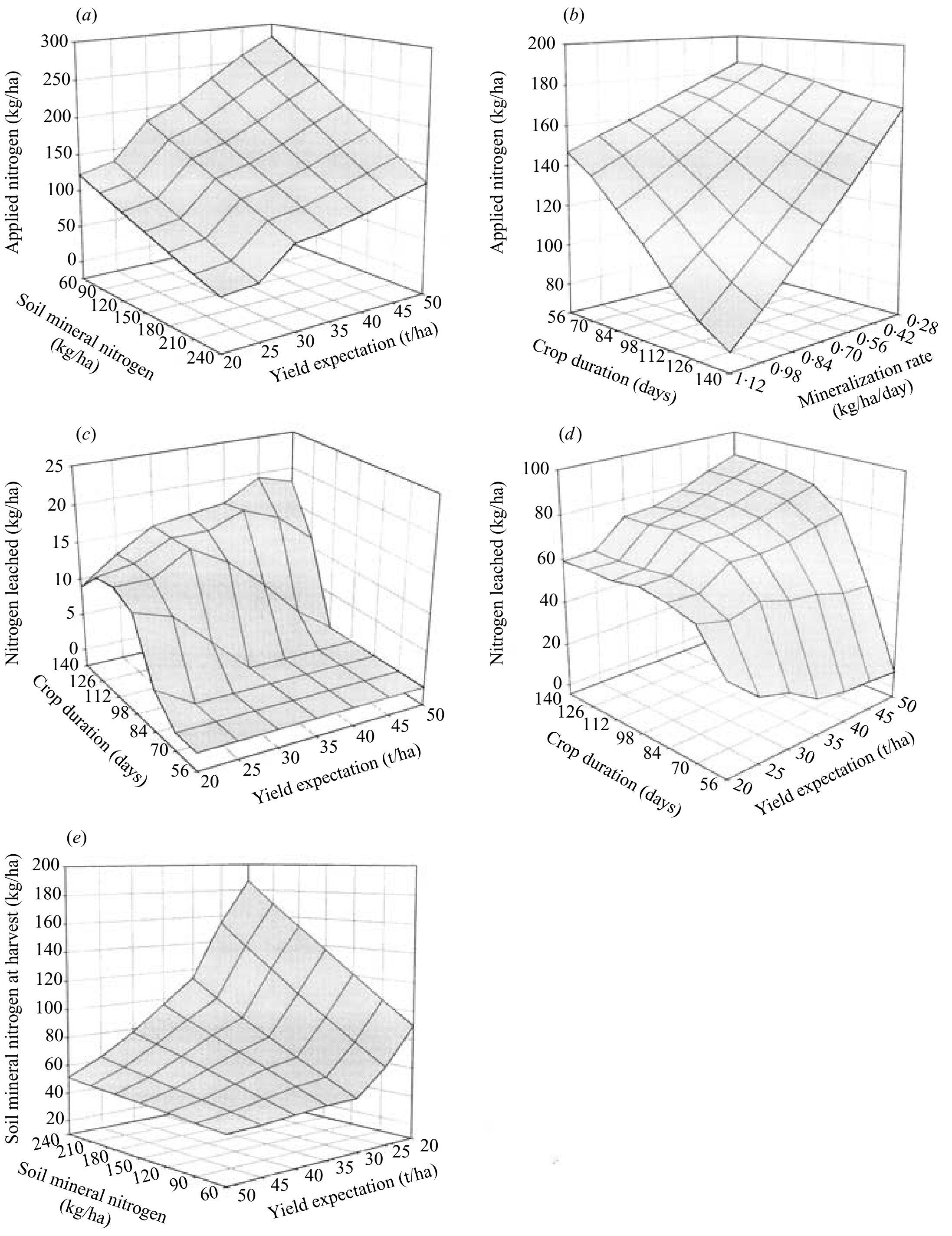

Fig. 3. Effects of joint variation of (*a*) soil mineral N and yield expectation on applied N to achieve 99% of maximum dry weight, for average rainfall on sandy loam soil, (*b*) mineralization rate and crop duration on applied N to achieve 99% of maximum dry weight, for average rainfall on sandy loam soil, (*c*) yield expectation and crop duration on the amount of NO_3-N leached from 0–30 cm, for average rainfall on sandy soil, (*d*) yield expectation and crop duration on NO_3-N leached from 0–30 cm, for high rainfall on sandy soil, and (*e*) soil mineral N and yield expectation on soil mineral N in 0–90 cm at harvest, for average rainfall on sandy loam soil.

response surfaces (for two- and three-factor interactions), together with tables showing the values at the extremes of the factor combinations.

Having assessed the sensitivity of the simulation model to variation in the important input parameters identified above, a second series of calculations was performed to determine the effects of incorrectly specifying the parameter values. For each combination of input factor levels, output variables were calculated, again by cubic interpolation, at the optimum level of applied N fertilizer predicted at the mid-point values of all four factors. This allowed the assessment of the effect of both under- and over-estimating the values of each of the input factors. The resulting data were analysed using the same approach as described above, with response curves and surfaces constructed at the mid-point values of the other factors, rather than using mean values across the levels of the other factors as for the first set of data.

RESULTS AND DISCUSSION

Nitrogen recommendations

Predicted levels of applied fertilizer N required to achieve 99% of the maximum yield were around 145 kg/ha at the mid-point of each factor in dry and average conditions with little effect of soil type (Appendix A). In wet conditions, soil type only had an influence on the lightest soils where it was estimated that around 160 kg/ha N was required at the mid-point of each factor (Appendix A). This suggested less efficient use of N on light soils because of leaching losses in wet conditions. Compared with MAFF fertilizer recommendations (MAFF 2000) these average rates of N application compare with more fertile, SNS index 3 or 4 conditions in which soils would typically supply around 101–160 kg/ha from mineral N to 90 cm and mineralization from soil organic matter.

Individually, there were significant effects for all four input factors on the N recommendation to produce 99% of the maximum dry weight yield (Table 4*a*). The patterns of response to the factors were similar for all nine combinations of rainfall and soil type, as illustrated in Fig. 2*a* for average rainfall on sandy loam soil. Where the response to a factor is almost linear (as seen for all four factors in Fig. 2*a*), the sum of squares associated with the term is almost entirely attributable to the linear contrast, a larger value indicating a steeper slope. As a consequence the relative sizes of the variance ratios give an indication of the relative importance of each input factor, a larger ratio generally indicating a greater response.

The greatest effect on N recommendation was caused by changes in yield expectation (Table 4*a*, Fig. 2*a*), with on average a change of 1% in N recommendation for each 1% change in yield expectation.

Table 5. *N recommendations for combinations of the soil mineral N and yield expectation factors, at the 'corners' and centre of the parameter space*

Soil mineral N kg/ha		150	60	60	240	240
Yield expectation t/ha		35	20	50	20	50
Rainfall	Soil type					
Low	Sand	145	121	285	39	127
Low	Sandy loam	145	122	285	45	128
Low	Silt loam	145	122	285	45	127
Average	Sand	144	120	282	38	126
Average	Sandy loam	145	122	283	44	126
Average	Silt loam	144	122	283	45	125
High	Sand	161	140	288	69	146
High	Sandy loam	149	124	285	54	134
High	Silt loam	146	122	284	49	130

Although the effect was not entirely linear, an increase in yield expectation did result in an increased N requirement. The non-linearity between reductions of 28 and 14% of marketable yield (corresponding to 25 and 30 t/ha yield) reflects the increased N uptake achieved at low yield levels due to the increased horizontal and vertical distribution of the root system. The other three factors all cause similar linear responses, with soil mineral N causing the greatest response (Fig. 2*a*). However, even large changes ($\pm 60\%$) in mineralization rate caused changes in N recommendation of less than 25%. Increases in all three factors (soil mineral N, mineralization rate and duration of growth) can be thought of as representing an increase in soil N availability. As the soil availability of N increased, the requirement for applied N decreased.

For all soil type/rainfall combinations, the only significant interaction effect was between soil mineral N and expected yield, though in all cases this interaction was considerably less important than any of the factor main effects (Table 4*a*). The pattern of this interaction was similar for all soil/rainfall combinations, and is illustrated in Fig. 3*a* for average rainfall on sandy loam soil. The response to increasing soil mineral N is much greater for high yield expectation than where the yield expectation is low, whilst the response to increasing yield expectation is greater with less soil mineral N. Table 5 contains the N recommendations at the 'corners' and centre of the 'parameter space'. The maximum recommendation, required for low soil mineral N and high yield expectation, is almost identical for all nine soil type/rainfall combinations. The patterns for the low and average rainfall scenarios are also very similar, the only variation being in the N recommendation for high soil mineral N (240 kg/ha) and low yield expectation (20 t/ha), where the recommendation is lower for sand than for either of the other soil types.

For the high rainfall scenarios N recommendations were generally higher than for the other rainfall scenarios, most notably for sandy soils.

The benefit of applying the recommended N level is represented by yield response, taken to be the difference between the yield at the 'optimum' level of applied N and that for zero applied N. Analogous to the analysis of N recommendations, there were significant main effects of all four input factors on the yield response (Table 4*b*). Again, the greatest effect on this difference in yield response was caused by changes in yield expectation, with an increase in yield expectation resulting in an increase in achieved yield (Fig. 2*b*), as might be anticipated. Increases in each of the other three input factors (soil mineral N, mineralization rate, crop duration), resulted in a decrease in yield response. The yield expectation factor affects the maximum achievable yield for a given set of parameters, whilst the other three input factors affect the soil availability of N, and hence the yield achievable without applying fertilizer N.

Many systems rely simply on the assessment of soil mineral N to form the basis of N recommendations (see, for example, MacKenzie & Taureau (1997) and Geypens & Vendendriessche (1996)). These systems rely on measurements taken at a single time, either before or after planting, taking no account of the effects of changing conditions, on both the distribution and amount of soil mineral N in the soil profile. Rahn *et al.* (1996*a*) has shown the importance of taking such redistribution of mineral N into account for brassica crops. In particular they showed that where N was located deeper in the soil profile, fresh fertilizer N needed to be applied to achieve maximum yields. Many of the recommendation systems referred to in the introduction require estimates of soil mineralization rate, but the WELL_N model was relatively insensitive to quite large changes in mineralization rate (Fig. 3*b*). The effects of mineralization rate were larger for long season crops, short season crops with even fourfold changes in mineralization rate only showing a 25% change in recommendation rate. In addition Greenwood *et al.* (1996) suggested that the main field to field variations in N supply for soil were as a result of incorporation of fresh crop residues rather than changes in mineralization of N from soil organic matter. The WELL_N simulation model is able to predict variations in the release of N from crop residue materials, and the subsequent redistribution of N caused by rainfall events. As a result, N recommendations provided by the model are more targeted to the availability of N in specific situations (Rahn *et al.* 1996*b*).

Redistribution of nitrogen

Leaching can reduce amounts of available N in the root zone of crops thereby reducing the efficiency of N use, and hence increasing the amounts of N to be supplied by fertilizer. Using the simulation model it was calculated that more movement of NO_3-N occurred on lighter soils in wetter seasons (Appendix A), but only small amounts (< 11 kg/ha) were calculated to have been moved below 90 cm. Where leaching below 90 cm was indicated, the dominant effects were for soil mineral N and duration in growth (Table 4*c*): increases in both generally leading to increased levels of leaching.

Leaching below 30 cm would affect the availability of N to the shallow roots of young crops, but was not calculated on any soil given low rainfall, and only on sandy soils in average rainfall conditions. For this scenario, the main response was to crop duration (Table 4*d*, Fig. 2*c*). Higher levels of leaching were calculated for longer season crops, particularly for high yielding crops where nearly 20 kg/ha N was moved for a 140-day crop compared with less than 4 kg/ha N for a 98-day crop and no leaching for a 56-day crop (Fig. 3*c*). This could be explained by the increased risk of leaching with the larger amounts of N needed for higher yields, being applied as a single dressing before crops grew away. Higher leaching levels were calculated for high rainfall on all soils, with simulations indicating up to 84 kg/ha N being leached for sandy soils (Fig. 3*d*). There were significant effects on leaching levels below 30 cm for all four factors on all three soils, with the exception of mineralization rate on silt loam soils (Table 4*d*).

On both sand and sandy loam soils, NO_3-N leaching below 30 cm generally declined with both increasing soil mineral N and mineralization rate, whilst on silt loam soils there was little effect of mineralization rate and leaching increased with increased soil mineral N. The minimal effect of varying mineralization rate on the amount of leaching below 30 cm can be explained in that the larger soil supplying capacity was matched by a lower requirement for applied fertilizer N.

Leaching below 30 cm will affect the amount of N available to young crops, and similar effects have been both simulated and measured in field situations (Lord & Bland 1991), and measured in undisturbed columns of light soil (Esala & Leppänen 1998). Such movement of N out of the immediate rooting zone of young crops may require additional amounts of N to be applied to overcome initial shortages. However, it is also likely that the crops will subsequently recover some of the N leached below 30 cm, when roots have been developed below this depth. Strategies such as splitting of fertilizer and the application of placed fertilizer by banding or as starter fertilizer (Stone 2000) may reduce the amounts of N lost by leaching. However the existing model requires further adaptation before it can be used to take account of either banded application of fertilizer or the use of starter fertilizers.

Potentially leachable soil mineral nitrogen at harvest

Soil mineral N at harvest can be considered as an indication of the potential for environmental pollution through leaching during the following winter.

For all weather/soil type scenarios, the only significant main factor effect on mineral N at harvest in the 0–30 cm layer was due to yield expectation (Table 4*e*). Substantial levels of mineral N at harvest were simulated for low yield expectations (20 or 25 t/ha) with no effect of yield expectation above these levels (Fig. 2*e*). A number of minor interactions were indicated, but even for the largest of these (the yield expectation by duration of growth interaction on average or high rainfall on sandy soils), the effect only appears as a minor modification of the main effect of yield expectation.

Both soil mineral N before planting and yield expectation had significant effects on soil mineral N at harvest in the 0–90 cm layer for all weather/soil type scenarios (Table 4*f*). Both effects, however, are modified by the effect of the other factor, so that the interaction between the two factors best illustrates the pattern of response (Fig. 3*e*). In general, as soil mineral N before planting increases, the level of soil mineral N at harvest increases, but with a larger response to soil mineral N before planting when the yield expectation is lower. Similarly, in general, an increase in yield expectation resulted in a decline in soil mineral N at harvest, with the greatest differences seen at high levels of soil mineral N before planting.

Soil mineral N left at harvest should be minimized to reduce the risks of subsequent leaching of N to the water table (Rice *et al.* 1995). The amount of soil mineral N in the top 30 cm provides some indication of the efficiency of the crops in using N. If yield levels were high, little mineral N was left at harvest and there was little effect of soil mineral N because N was used well by the crop. Where maximum yields were low, N was used inefficiently and where planting mineral N was higher than needed to supply the needs of the crop, mineral N levels at harvest were very high. Initial distribution of soil mineral N can also affect crop response (Rahn *et al.* 1996*a*). Decision support systems, such as WELL_N offer the opportunity to take account of the actual distribution of soil mineral N before planting (Rahn *et al.* 1996*b*). Where initial mineral N is distributed at lower layers in the soil profile WELL_N is able to allow for the increased risk of leaching during the growing season. Where N supply balances crop requirements, mineral N levels remaining at harvest are minimized (Prins *et al.* 1988, Davies & Sylvester-Bradley 1995).

The impact of incorrect nitrogen recommendations

The sensitivity analysis described above has shown the dominant effects of soil mineral N at planting and yield expectation on both the recommended level of applied N and two key output variables. One of these, the yield response, relates to the culture of the crop, and the second, the amount of potentially leachable soil mineral N at harvest, relates to environmental issues. The impact of the application of incorrect fertilizer recommendations was assessed by simulating both yield achieved and soil mineral N at harvest for the range of input parameter values, but with the level of applied fertilizer fixed at that recommended at the mid-point values of all four input factors.

On the sandy loam soil with average rainfall, the recommendation for applied N at the mid-point values of all four input factors (Table 2) was 147 kg/ha, giving a yield within 99% of 35 t/ha, and leaving 70 kg/ha soil mineral N (0–90 cm) at harvest. The predicted losses in achieved yield and gains in soil mineral N (0–90 cm) at harvest due to application of N at this level are shown for combinations of input factor values for yield expectation and soil mineral N before planting in Figs 4*a* and 4*b*, respectively.

Reductions in achieved yield with 147 kg/ha N were confined to situations where either yield expectation was underestimated (true values > 35 t/ha) or soil mineral N before planting was overestimated (true values < 150 kg/ha), or both (Fig. 4*a*). These situations coincided with those where the correct recommended applied N level exceeded that at the mid-point values of the input factors. Where soil mineral N before planting was underestimated (true values > 150 kg/ha), yield losses only occurred where yield expectation was badly underestimated. Similarly, where yield expectation was overestimated (true values < 35 t/ha), yield losses only occurred where soil mineral N before planting was badly overestimated. The greatest yield loss occurred where yield expectation should have been 50 t/ha (rather than 35 t/ha) and soil mineral N before planting should have been 60 kg/ha (rather than 150 kg/ha). The consequent reduction in applied N from 286 kg/ha to 147 kg/ha resulted in a yield loss of 7·9 t/ha (about 20% of the potential yield). Where yield expectation was underestimated (35 t/ha rather than 50 t/ha) but soil mineral N before planting is correct, the reduction in applied N from 208 kg/ha to 147 kg/ha resulted in a yield loss of 2·6 t/ha. Similarly, where soil mineral N before planting was overestimated (150 kg/ha rather than 60 kg/ha), but yield expectation is correct, the reduction in applied N from 203 kg/ha to 147 kg/ha resulted in a yield loss of 2·9 t/ha.

The slight increase in achieved yield where yield expectation was overestimated and soil mineral N before planting is underestimated is caused by more N being applied than would be correctly recommended and the achieved yield reaching the maximum value rather than 99% of the maximum.

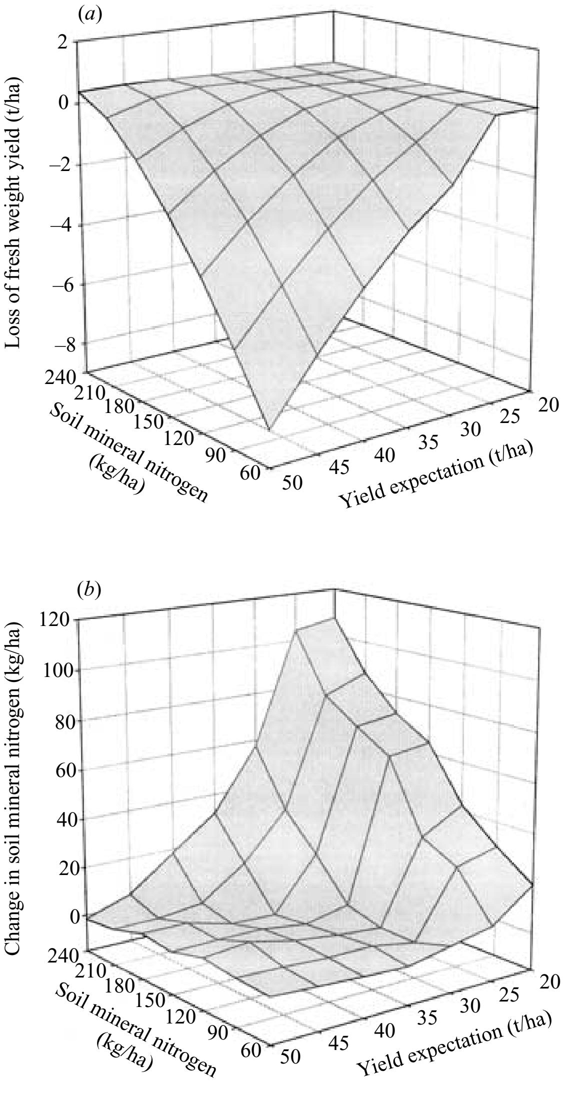

Fig. 4. The impact of incorrect values of soil mineral N and yield expectation on (*a*) achieved fresh weight yield and (*b*) soil mineral N at harvest in 0–90 cm. Applied N (147 kg/ha N) based on 150 kg/ha mineral N, a yield expectation of 35 t/ha for average rainfall, a crop duration of 98 days, and a mineralization rate of 0·70 kg/ha/day @ 15·9 °C on sandy loam soil.

Whilst overestimating yield expectation or underestimating soil mineral N before planting have relatively little impact on the achieved crop yield, these errors can have a substantial impact on the risk of environmental pollution, as measured by the increase in soil mineral N (0–90 cm) at harvest (Fig. 4*b*). Significant increases in soil mineral N at harvest only occurred where the correct recommended applied N level was significantly less than 147 kg/ha. The most dramatic increase was simulated where yield expectation should have been 20 t/ha (rather than 35 t/ha) and where soil mineral N before planting should have been 240 kg/ha (rather than 150 kg/ha). The consequent increase in applied N from 37 kg/ha to 147 kg/ha resulted in an additional 108 kg/ha soil mineral N remaining at harvest (leaving a total of 285 kg/ha potentially leachable N).

The impact of underestimating yield expectation or overestimating soil mineral N before planting was environmentally friendly, with little additional soil mineral N remaining at harvest, though with the associated yield losses described above.

PRACTICAL IMPLICATIONS

WELL_N provides a dynamic system for providing N recommendations for cauliflower crops. It is sensitive to those factors which are easily measurable by the grower. Errors in measurements of mineralization rate make little difference to fertilizer recommendations especially for short season crops. The model is highly sensitive to measurements of soil mineral N before planting and estimation of yield expectation. Measurements of soil mineral N before planting are relatively easily made, and growers often subjectively estimate yield expectation based on previous yield performance in the field. However, there is little in the literature to support an objective assessment of yield expectation, except in limited circumstances (Campbell *et al.* 1997).

The modelling approach has also enabled possible management strategies for the reduction of nitrate leaching from crops whilst maintaining production to be quantified. For example it would be an advantage to grow higher-yielding, faster-growing crops. Even though such crops have a larger fertilizer requirement they do deplete soil mineral N to a lower level and, providing that the residues of crop are well managed, this should reduce the risk of leaching (Rahn *et al.* 1996*a*). It would seem to be important to choose crop parameters that encourage a more complete uptake of N particularly in wet seasons. Significant loss of mineral N can occur from the rooting zone of shallow rooted crops. Strategies to target or split applications of N application to reduce N losses would be beneficial. From a leaching point of view it would also be useful to consider closer row spacing to ensure more complete exploration of the soil surface.

Financial support from the UK Ministry of Agriculture, Fisheries and Food for strategic research and Horticultural Development Council for the development work is greatly appreciated.

Appendix A. Mean responses at the mid-points of the input factors for each of the soil-type by weather (rainfall) combinations: DSA, dry sand; DSAL, dry sandy loam; DSIL, dry silt loam; ASA, average sand; ASAL, average sandy loam; ASIL, average silt loam; WSA, wet sand; WSAL, wet sandy loam; WSIL, wet silt loam

	DSA	DSAL	DSIL	ASA	ASAL	ASIL	WSA	WSAL	WSIL
Soil mineral N									
N requirement for 99% yield	143	144	144	142	143	143	159	148	145
Achieved yield at applied N	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3
Yield response	2·3	2·5	2·5	2·3	2·4	2·5	2·6	2·6	2·6
N uptake at applied N	205	205	205	205	205	205	207	206	206
N leached below 30 cm	0	0	0	6	0	0	60	20	5
N leached below 90 cm	0	0	0	0	0	0	11	4	2
Mineral N at harvest in 0–30 cm	20	20	20	20	20	20	19	19	20
Mineral N at harvest in 0–90 cm	79	79	79	75	79	79	82	80	79
Mineralization rate									
N requirement for 99% yield	143	144	144	143	143	143	160	149	146
Achieved yield at applied N	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3
Yield response	2·3	2·5	2·5	2·3	2·4	2·5	2·6	2·6	2·6
N uptake at applied N	205	205	205	205	206	206	207	206	206
N leached below 30 cm	0	0	0	6	0	0	61	20	5
N leached below 90 cm	0	0	0	0	0	0	11	4	2
Mineral N at harvest in 0–30 cm	20	20	20	20	20	20	19	19	20
Mineral N at harvest in 0–90 cm	79	80	80	79	79	79	82	80	80
Harvest yield									
N requirement for 99% yield	146	146	146	146	146	146	162	151	147
Achieved yield at applied N	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3
Yield response	2·4	2·5	2·6	2·4	2·5	2·5	2·7	2·7	2·6
N uptake at applied N	205	205	205	206	206	206	209	206	206
N leached below 30 cm	0	0	0	6	0	0	61	20	5
N leached below 90 cm	0	0	0	0	0	0	11	4	2
Mineral N at harvest in 0–30 cm	14	14	14	14	14	14	14	14	14
Mineral N at harvest in 0–90 cm	71	71	71	71	71	71	72	71	71
Duration of growth									
N requirement for 99% yield	144	145	145	144	144	144	164	150	146
Achieved yield at applied N	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3	5·3
Yield response	2·3	2·5	2·5	2·3	2·4	2·5	2·6	2·6	2·6
N uptake at applied N	205	205	205	206	206	206	208	206	206
N leached below 30 cm	0	0	0	4	0	0	72	25	6
N leached below 90 cm	0	0	0	0	0	0	13	6	3
Mineral N at harvest in 0–30 cm	20	20	20	19	20	20	19	19	19
Mineral N at harvest in 0–90 cm	79	79	79	78	79	79	83	80	79

REFERENCES

BURNS, I. G. (1974). A model for predicting the redistribution of salts applied to fallow soils after excess rainfall evaporation. *Journal of Soil Science* **25**, 165–168.

BURNS, I. G., RAHN, C. R., GREENWOOD, D. J., DRAYCOTT, A. & RICHARDSON, A. S. (1997). A user friendly decision support system for adjusting N fertilizer requirements to local conditions. In *Proceedings of a Conference on Managing Soil Fertility for Intensive Vegetable Production Systems in Asia*, 4–10 November 1996. Taiwan: AVRDC, pp. 314–324.

CAMPBELL, C. A., SELLES, F., ZENTNER, R. P., MCCONKEY, B. G., BRANDT, S. A. & MCKENZIE, R. C. (1997). Regression model for predicting yield of hard red spring wheat grown on stubble in semiarid prairie. *Canadian Journal of Plant Science* **77**, 43–52.

DAVIES, D. B. & SYLVESTER-BRADLEY, R. (1995). The contribution of fertiliser nitrogen to leachable nitrogen in the UK: A review. *Journal of the Science of Food and Agriculture* **68**, 399–406.

ESALA, M. & LEPPÄNEN, A. (1998). Leaching of 15N-labeled fertilizer nitrate in undisturbed soil columns after simulated heavy rainfall. *Communications in Soil Science and Plant Analysis* **29**, 1221–1238.

EVERAARTS, A. P. (1994). Nitrogen fertilization and head rot in broccoli. *Netherlands Journal of Agricultural Science* **42**, 195–201.

Fink, M. & Scharpf, H.-C. (1993). N Expert – A decision support system for vegetable fertilization in the field. *Acta Horiculturae* **339**, 67–74.

Genstat 5 Committee (1993). *Genstat 5 Release 3 Reference Manual*. Oxford, UK: Clarendon Press.

Geypens, M. & Vendenriessche, H. (1996). Advisory systems for nitrogen fertiliser recommendations. *Plant and Soil* **181**, 31–38.

Greenwood, D. J. & Draycott, A. (1989). Experimental validation of an N-response model for widely different crops. *Fertilizer Research* **18**, 153–174.

Greenwood, D. J., Gerwitz, A., Stone, D. A. & Barnes, A. (1982). Root development of vegetable crops. *Plant and Soil* **68**, 75–96.

Greenwood, D. J., Neeteson, J. J. & Draycott, A. (1986). Quantitative relationships for the dependence of growth rate of arable crops on their nitrogen content, dry weight and aerial environment. *Plant and Soil* **91**, 281–301.

Greenwood, D. J., Verstraeten, L. M. J. & Draycott, A. (1987). Response of winter wheat to N-fertilizer: Quantitative relations for components of growth. *Fertilizer Research* **12**, 119–137.

Greenwood, D. J., Kubo, K., Burns, I. G. & Draycott, A. (1989). Apparent recovery of fertilizer N by vegetable crops. *Soil Science and Plant Nutrition* **35**, 367–381.

Greenwood, D. J., Stone, D. A. & Draycott, A. (1990). Weather, nitrogen-supply and growth rate of field vegetables. *Plant and Soil* **124**, 297–301.

Greenwood, D. J., Gastal, F., Lemaire, G., Draycott, A., Millard, P. & Neeteson, J. J. (1991). Growth rate and % N of field grown crops: theory and experiments. *Annals of Botany* **67**, 181–190.

Greenwood, D. J., Neeteson, J. J., Draycott, A., Wijnen, G. & Stone, D. A. (1992). Measurement and simulation of the effects of N-fertilizer on growth, plant composition and distribution of soil mineral-N in nationwide onion experiments. *Fertilizer Research* **31**, 305–318.

Greenwood, D. G., Rahn, C. R., Draycott, A. & Paterson, C. (1996). Modelling and measurement of the effects of fertilizer-N and crop residue incorporation on N-dynamics in vegetable cropping. *Soil Use and Management* **12**, 13–24.

Johnson, L. W. & Riess, R. D. (1982). *Numerical Analysis (2nd edition)* – Section 5.2.6. Reading, MA: Addison-Wesley.

Lorenz, H. P., Schlaghecken, J., Engl, G., Maync, A., Ziegler, J. & Strohmeyer, K. (1989). Kulturbegleitendes Nmin sollwert (KNS) – System. Mainz: Ministerium für Landwirtschaft, Weinbau und Forsten.

Lord, E. I. & Bland, G. (1991). Leaching of spring-applied fertilizer nitrogen: measurement and simulation. *Soil Use and Management* **7**, 110–114.

Ministry for Agriculture, Food and Fisheries (2000). *Fertilizer Recommendations* Seventh Edition, Reference Book 209. London: HMSO.

MacKenzie, G. H. & Taureau, J. C. (1997). Recommendation systems for nitrogen – A review. *Paper read before the Fertiliser Society of London on 11 December 1997. Proceedings No 403, The Fertilizer Society*, pp. 1–51.

McKay, M. D., Conover, W. J. & Beckman, R. J. (1979). A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics* **21**, 239–245.

Neeteson, J. J., Greenwood, D. J. & Draycott, A. (1987). A dynamic model to predict yield and optimum nitrogen fertiliser application rate for potatoes. *Paper read before the Fertiliser Society of London on 10 December 1987. Proceedings No 262, The Fertiliser Society*, pp. 1–29.

Prins, W. H., Dilz, K. & Neeteson, J. J. (1988). Current recommendations for nitrogen fertilisation within the EEC in relation to nitrate leaching. *Proceedings No 276, The Fertiliser Society of London*, UK, pp. 3–27.

Rahn, C. R., Paterson, C. D. & Vaidyanathan, L. V. V. (1993). Improving the use of nitrogen in brassica rotations. *Acta Horticulturae* **339**, 207–218.

Rahn, C. R., Paterson, C. D., Willison, T. & Lillywhite, R. D. (1996a). The fate of nitrogen from brassica crop residues in intensive cropping rotations. In *Nitrogen Supply and Nitrogen Fixation of Crops for Cool and Wet Climates*. Proceedings of a COST 814 Workshop held at the Norwegian Crop Research Institute (Planteforsk) Holt Research Centre, Tromso, 7–9 September 1995 (Ed. R. Samuelsen *et al.*), pp. 219–226. Luxembourg: Office of Official Publications of the European Communities.

Rahn, C. R., Greenwood, D. J. & Draycott, A. (1996*b*). Prediction of nitrogen fertiliser requirement with HRI WELL_N Computer Model. In *Proceedings of 8th Nitrogen Workshop, Ghent, 5–8 September 1994*. In *Progress in Nitrogen Cycling Studies*, pp. 255–258. Dordrecht: Kluwer.

Rice, C. W., Havilin, J. L. & Schepers, J. S. (1995). Rational nitrogen fertilization in intensive cropping systems. *Fertilizer Research* **42**, 89–97.

Riley, H. & Guttormsen, G. (1993). N requirements of cabbage crops grown in contrasting soils. I: Field trials. *Norwegian Journal of Agricultural Sciences* **7**, 275–291.

Riley, H. & Guttormsen, G. (1994). N requirements of cabbage crops grown on contrasting soils in southern Norway. II. Model predictions. *Norwegian Journal of Agricultural Sciences* **8**, 99–113.

Shepherd, M. A. (1993). Measurement of soil mineral nitrogen to predict the response of winter wheat to fertiliser nitrogen after application of organic manures or after ploughed – out grass. *Journal of Agricultural Science, Cambridge* **121**, 223–231.

Sokal, R. R. & Rohlf, F. J. (1995). *Biometry: The Principles and Practice of Statistics in Biological Research (3rd Edition)* – Section 16.5. New York, USA: W. H. Freeman & Co.

Stone, D. A. (2000). The effects of starter fertilizers on the growth and nitrogen use efficiency of onion and lettuce. *Soil Use and Management* **16**, 42–48.

Sutherland, R. A., Wright, C. C., Verstraeten, L. M. J. & Greenwood, D. J. (1986). The deficiency of the 'economic optimum' application for evaluating models which predict crop yield response to nitrogen fertiliser. *Fertilizer Research* **10**, 251–262.

Van Veen, J. A. & Frissel, D. E. (1981). Simulation model of the behaviour of N in soil. In *Simulation of Nitrogen Behaviour of Soil Plant Systems* (Eds M. J. Frissel & J. A. Van Veen), pp. 126–144. Wageningen: Centre for Agricultural Publishing and Documentation.