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PROJECT REPORT No. 258

DECISION SUPPORT SYSTEM TO DESIGN WHOLE FARM ROTATIONS THAT OPTIMISE THE USE OF AVAILABLE NITROGEN IN MIXED ARABLE AND HORTICULTURAL SYSTEMS: ON-FARM TESTING

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by

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8. Appendices:
    Appendix A – Field Trial Response Data
    Appendix B – Evaluation of WELL_N and SUNDIAL-FRS at each field site

These appendices consist of about 160 pages of site data for 1998 and 1999, and are available on request from Business Services, HGCA, Caledonia House, 223 Pentonville Road, London N1 9HY, at a cost of £8.00.

PRACTICAL SECTION FOR FARMERS AND GROWERS

Background

Why do we need models? A significant barrier to more efficient use of nitrogen fertiliser by arable farmers and horticultural growers is the lack of information on seasonal, soil-related and cultural variations in the supply of mineral nitrogen by the soil and the requirements for nutrients by the crop. Researchers have identified many processes of nitrogen transformation and the controls exerted by climate and soil conditions. Models provide a tool for making practical use of this huge body of information and could be of enormous value in providing fertiliser recommendations and planning crop rotations on working farms.

Which model? There are essentially two types of model: static and dynamic. A static model is a one stage calculation which takes no account of progress of the soil/crop system with time. By contrast, a dynamic model recalculates the state of the soil/crop system throughout the simulation, according to specific climate and soil conditions. Most currently available fertiliser recommendation systems use static models: These include MAFF Reference Book 209; the ADAS system, FERTIPLAN; and NCYCLE, the system developed at IGER-North Wyke for grassland. Because a dynamic model is able to respond to changes in climatic and soil conditions, the new generation of fertiliser recommendation systems may be based on dynamic models: WELL_N, developed at HRI-Wellesbourne, and SUNDIAL, developed at IACR Rothamsted are two such models.

How do dynamic fertiliser recommendation systems work? The calculated crop nitrogen offtake and nitrate leaching are used by the fertiliser recommendation system to determine a fertiliser recommendation that minimises nitrate losses whilst maintaining crop productivity. The WELL_N and SUNDIAL models use different approaches to calculate the values needed according to specified crop management, soil and weather conditions. Both models include a description of all major processes of nitrogen turnover in the soil/crop system. Inputs are by fertiliser applications and atmospheric deposition. Available soil nitrogen is taken up by the growing crop, and returned to the soil as crop debris. Crop debris decomposes and either releases or uses up available nitrogen. Nitrogen may be lost from the soil by leaching, denitrification or volatilisation. SUNDIAL includes a detailed description of soil organic matter decomposition and allows inputs by organic manures. The WELL_N model incorporates a more concise description of the soil, but a more detailed simulation of crop growth. It includes many simple widely applicable relationships for calculating N demand of the crop, amount of N taken up and its partitioning within the plant, automatically adjusting the results for changes in the amount and distribution of mineral N available to a crop.

Because the 2 models have been developed along separate, but parallel lines, there are great potential benefits from combining the models into a single package. The objectives of this project were

- to develop a fertiliser recommendation system based on the SUNDIAL and WELL_N models; and
- to establish field trials on working farms across the UK to test how well the fertiliser recommendation system works.

Development of Nitrogen-FRS

Nitrogen-FRS - Two dynamic N turnover models, SUNDIAL and WELL_N have been combined in a single package with a static model based on MAFF Reference Book 209 (MAFF, 1994). The package, referred to in this report as “Nitrogen-FRS”, allows the user to manually select the model, but also has the potential to automatically set the optimum model for use under particular field conditions. The system is Windows based and fully supported by default values, allowing simulations to be run quickly and easily with minimum requirement for user inputs. If more season and site specific data on crop management, soil description, weather data or manure inputs are entered, the dynamic models have the potential to provide season and site specific N fertiliser recommendations. The system provides further support for planning N use by presenting balance sheets, graphical plots and flow charts showing changes in the N status of the soil/crop system over time. Weather data can be entered manually or default weather is provided for SUNDIAL by an in-built weather generator. Development of a weather generator to provide default weather data for WELL_N requires further funding. It is envisaged that the system will be made available both as a standalone and a DESSAC compatible version. This is essential if the system is to make use of the additional functionality of DESSAC, while remaining accessible to DESSAC and non-DESSAC users alike.

Database of Measurements - In order to evaluate the likely accuracy of the fertiliser recommendations and simulations of N turnover on working farms, and to identify which model should be used to simulate a particular crop, field trials were run over 2 seasons on 37 sites across the UK with a range of arable and horticultural crops. Spring and harvest soil mineral N was measured at 0-30cm, 30-60cm and 60-90cm. Whole crops were sampled at harvest and analysed for N content. A database was constructed to store the descriptions and results of the field trials, and make it readily available for future use. This was designed with a hierarchical structure, starting with site identifiers (name of farmer etc.) expanding to general site data (e.g. location, soil type and previous husbandry details), and further to incorporate data which varies over time, and finally to data collected from each experimental plot.

Nitrogen Response -These trials were planned to evaluate the performance of the SUNDIAL-FRS and WELL_N fertiliser recommendation systems. In practice, they have told us more about nitrogen response on working farms than about the functioning of the models. No response to nitrogen application was observed in 14 trials out of a total of 64. This was partly because inappropriate sites were not excluded in advance, despite laying down clear site selection criteria. At sites 9/99, 15/98 and 15/99 this was due to applications of manure, in which case an optimum of zero is quite reasonable. Other sites (19/99 and 2/98) received inadvertent applications of fertiliser N. Nitrogen uptake, where no fertiliser was applied, varied from 21 to 266 kg N ha^{-1}, reflecting inherent differences in the fertility of the soil and the period and duration of crop growth. Surprisingly there was no significant relationship between spring soil mineral nitrogen and crop nitrogen uptake on zero plots, even when only the combinable crops or winter wheat alone were included. This suggests that soil characteristics more closely related to soil nitrogen supply, such as soil organic nitrogen, may be important input data. The optimum nitrogen fertiliser application (with an estimate of its 95% confidence interval) could be determined from a linear plus exponential relationship, for only 36% (23) of the trials. In nine trials no optimum could be fitted, possibly because the optimum was below the range of N rates used. In some cases, this may be due to high levels of fertiliser N and manure being used on commercial farms in previous years, where maximum productivity is paramount. It indicates an inefficient system that may be detrimental to the environment. It is particularly difficult to evaluate the performance of the models on these sites where an optimum N rate cannot be established (the optimum is zero if there is no response to N).

Shortage of Data - The models have been run assuming default soil conditions and using a maximum of five years of cropping history at the arable sites, and often only one or two years of cropping history at the horticultural sites. These limited data inputs cannot account for the changes in soil nitrogen supply that occur under a long-term high nitrogen input regime. This problem affects dynamic fertiliser recommendation systems using minimal input data in the same way as it affects static systems such as RB209. The effect is likely to be experienced by a large proportion of farmers attempting to achieve maximum productivity. High nitrogen input regimes can only be adequately described using a dynamic simulation model, driven by a suite of field diagnostics or using field records of more than 10 years. Where farmers do not have adequate long-term records, further work to develop field diagnostic measurements that can be used to drive models will be essential for future improvements in precision.

Spatial Variability – In some trials, the difficulty in determining an optimum nitrogen application rate appears to be due to spatial variability in the field. Spatial variability is an inevitable feature at some sites due to factors such as field history, underlying soil type, drainage conditions and field gradient. Methods for accounting for spatial variability in fertiliser recommendation are urgently needed. This could be done by driving the model using measures of the previous years yield combined with remotely sensed field diagnostics. In the longer term, a model including lateral movement of nitrogen due to the gradient may be beneficial. At some sites, increased precision in fertiliser applications will only be possible by developing advanced methods to describe the spatial variability of the soil.

Evaluation of Models - Evaluation at both the vegetable and arable sites indicated that the fertiliser recommendations from SUNDIAL-FRS, WELL_N and RB209 resulted in similar crop yields. However, both WELL_N and SUNDIAL-FRS gave more accurate recommendations than RB209 or farm practice, thereby reducing fertiliser costs and wastage to the potential benefit of the environment. Using spring SMN measurements as diagnostics did not generally improve the recommendations in SUNDIAL-FRS, and was of little benefit in terms of yield. Further work is needed to develop the use of SMN as a field diagnostic. Overall, using actual weather and yield was of only small benefit.

Evaluation of Nitrogen-FRS -When all 3 models were combined into the single package, Nitrogen-FRS, the fertiliser recommendations were significantly better than farm practice. It should be emphasised that the farmers participating in the trials were highly skilled at selecting optimum application rates. They were very familiar with the conditions on their farms and had years of experience in determining the nitrogen fertiliser rate that should be applied. As a result, farm practice was highly correlated with the observed optimum N rate. However, Nitrogen-FRS consistently provided improved recommendations over farm practice. This indicates the success of combining the 3 nitrogen recommendation systems into a single package. Different approaches to fertiliser recommendation no longer need to compete: instead each helps the overall system to provide better recommendations. Since the initiation of this project the 7th edition of RB209 has been published (MAFF, 2000). This should also be incorporated into Nitrogen-FRS, to provide a single source of the latest information for both arable and vegetable crops. This system allows diverse recommendation systems to be combined into one decision support system and used together to improve the overall result.

Action Points

In order to make full use of dynamic simulation models, farmers and growers should (1) maintain accurate, long-term field records; (2) improve uniformity of fertiliser applications; (3) calibrate fertiliser spreaders; (4) measure yield; (5) record applications of organic wastes.

Potential Benefits

Accurate fertiliser recommendations are of clear benefit to:

• the farmer and grower - reducing costs of fertiliser, fuel and time
• the industry - maintaining yield and quality
• the environment - reducing leaching of nitrate to groundwater

Though a little more complex to operate than static systems, dynamic models are able to provide recommendations accounting for changes in weather conditions and management practices for specific fields or farms. Because a dynamic model includes a description of all major processes, the system provides access to the science underlying any recommendation, and may be used to assess associated risks.

SCIENTIFIC SECTION

1. Introduction

1.1. Background

A significant barrier to more efficient use of nitrogen (N) fertiliser by arable farmers and horticultural growers is the lack of information on the seasonal, soil-related and cultural variations in the supply of mineral N by the soil and the requirements for nutrients by the crop. Much of the necessary information can already be provided in a clear and flexible way for mainly arable crops by SUNDIAL (the Rothamsted model for SimUlation of Nitrogen Dynamics In Arable Land - Bradbury *et al.,* 1993.) and for mainly horticultural crops by WELL_N (based on the HRI N turnover model - Greenwood *et al.*, 1992). SUNDIAL has been constructed into a decision support system for fertiliser recommendation in previous work, funded by MAFF (NT1202 and NT2306). In this project, the WELL_N model has been incorporated into the existing decision support system, and field trials have been run to evaluate the performance of both models on working farms. This pilot project should facilitate the release of the decision support system to the farming community, so ensuring that the potential benefits of 150 years of research on N, crops and soil organic matter are passed directly to the farmer. In addition, an ACCESS database of the results of the field trials has been created for use in the current project as well as by future researchers. The database provides a unique and invaluable resource for evaluating the performance of fertiliser recommendation systems.

There are essentially two types of model: static models and dynamic models. A static model is a one-stage calculation that takes no account of progress of the soil/crop system with time. In contrast, a dynamic model recalculates the state of the soil/crop system throughout the simulation, according to specific climate and soil conditions. Most currently available fertiliser recommendation systems use static models: these include MAFF Reference Book 209 (MAFF, 1994); the ADAS system, FERTIPLAN; and NCYCLE, the system developed at IGER-North Wyke for grassland. Because a dynamic model is able to respond to changes in climatic and soil conditions, the new generation of fertiliser recommendation systems may be based on dynamic models: WELL_N, developed at HRI-Wellesbourne, and SUNDIAL, developed at IACR Rothamsted are two such models.

WELL_N is a computer program that provides improved recommendations and management advice for the use of N on a wide range of vegetable and some arable crops. The software was developed under MAFF and HDC funding and uses the HRI N response model to tailor the recommendations to the different weather, soil and cultural practices at each site. The model incorporates many simple widely applicable relationships for calculating the N demand of each crop, the amount of N taken up and its partitioning within the plant, automatically adjusting the results for changes in the amount and distribution of mineral N available to a crop. Inputs to the model include information about the crop, the soil, management practices and weather: most of these are readily available or can be estimated for individual sites. Options are available to run the model either using regional long-term average weather data to provide an initial recommendation before the crop is grown or using actual weather data recorded during crop growth to provide management advice on top dressing or irrigation requirements.

SUNDIAL was originally developed under funding from HGCA and has been developed through subsequent MAFF funding. It is a fully functional dynamic model of the N cycle under a range of different arable and some horticultural crops. Management scenarios may be described through a user-friendly interface using measurements that are available to the farmer or advisor. The model is designed to use weekly weather data. In predicting fertiliser requirements a weekly time step introduces fewer problems associated with predicting weather data due to temporal and spatial variability than a model with a short time step. The model can be used to predict the fertiliser requirements of a given crop with a specified yield. Alternatively the model may be tested by running the simulation retrospectively and comparing the results to measurements of soil mineral N or N offtake in the crop.

Although both SUNDIAL and WELL_N models have undergone extensive retrospective testing using data from controlled experiments, few trials have been undertaken to test their reliability under *real* farm conditions. There is, therefore a pressing need to test both models on working farms to check that proper account is taken of management practices which are not always replicated in experiments.

SUNDIAL and WELL_N have been developed along separate, but parallel lines, and so there are large benefits from combining both models into a single package. The package is referred as "Nitrogen-FRS" in this report. However, it should be noted that the name of the combined fertiliser recommendation system is still under discussion.

1.2. Aims and Work Plan

In this project, we aimed to incorporate WELL_N and SUNDIAL into a flexible decision support system for designing whole farm rotations to optimise the use of available N in mixed arable and horticultural systems. The system has been taken to working farms and horticultural enterprises across the UK and used to provide recommendations for selected crops using projected weather data. The accuracy of the recommendations has been assessed by comparison with the results of field trials at each site. The model performance was further evaluated by retrospective simulation using actual weather data recorded during the experiments.

The overall objectives of this 3 year project are summarised as:

(1) Devise a decision support system to optimise the use of available N.
(2) Establish field trials including mixed arable/horticultural rotations.
(3) Evaluate *on-farm* performance by simulating N turnover in the field trials.
(4) Use the evaluated system to design improved rotations.

The work plan for the project is given below:

1997

	APR		JUL	SEP
IACR		Devise decision support system for designing whole farm rotations	Establish AICC field sites	Set up trials for winter crops
HRI		Set up a database to hold details of rotations & results of analyses	Establish field sites identified by HDC	Provide fertiliser recommendations for specified rotation

1998

JAN	MAY	JUL	
IACR &	Take Soil Samples Set up trials for spring crops	Enter results into database	Take Soil and Crop Samples at Harvest
HRI	Provide fertiliser recommendations for specified rotation	Predict results of harvest sampling	Set up trials for winter crops & provide fertiliser recommendations for specified rotation

1999

JAN	MAY	JUL	
IACR &	Take Soil Samples Set up trials for spring crops	Enter results into database	Take Soil and Crop Samples at Harvest
HRI	Provide fertiliser recommendations for specified rotation	Predict results of harvest sampling	Start model evaluation

2000

JAN	APR	JUL	NOV
IACR &	Evaluation of model performance	Evaluation of model performance (Supplementary)	
HRI	Retrospective design of improved rotation & Report Writing	Retrospective design of improved rotation & Report Writing (Supplementary)	

2. Materials and Methods

2.1. Decision Support System

The decision support system has been written in Microsoft Visual C++, version 6.0. Microsoft Visual C++ was chosen because:

- it is an object-oriented language which can improve the efficiency of programming and memory management, and reduce running times;
- it provides a flexible Windows based graphical user interface, which is familiar to users; and
- it can avoid installation problems associated with use of Dynamically Linked Libraries as often experienced with languages such as Visual Basic.

To improve the memory management in SUNDIAL, the model was translated into C++ and incorporated into the decision support system as an object-oriented class. No memory problems were encountered with WELL_N, so the model was incorporated directly from Fortran code as local dynamically linked libraries. New grower interfaces were developed for WELL_N.

2.2. Database of Field Trials

The database was designed using Microsoft Access. This software was selected because:

- it is fully integrated into the Microsoft Office environment;

- it allows data to be stored and retrieved efficiently using a range of interchangeable formats for input into other software;
- it is a highly flexible system which allows future expansion of any database to include additional measurements (i.e. extra fields) and new data sets as they become available;
- it is well established and widely available to the scientific community; and
- it provides in-built design procedures to allow the creation of a compact clean storage system with visually attractive screens and automated functions.

2.3. On-Farm Nitrogen Response Trials

2.3.1. Site Selection

In selecting sites for the two years of the trials, the aim was to cover the principal vegetable and arable crops in their main growing areas. Selection was carried out with the assistance of consultants (from AICC or nominated by HDC). These consultants proposed farmers and growers who managed sites which had level or gently sloping topography and uniform soils. From the proposed shortlist, sites were chosen which gave a balance of crops and soil types. Ideal sites also had a known cropping history, mixed arable and horticultural rotations, easy access and had not used organic manures recently or been grassland in the previous ten years. Full details of the location of the trials are given in Table 1 and Figure 1. Four additional sites used in 1998, but lost when growers inadvertently harvested the trials before measurements were taken are omitted. The previous cropping and the cropping of the sites during the trials are given in Figure 2. Although it was planned to grow two crops in rotation, trials at six sites were discontinued in 1999 due to operational changes by the grower or, in one case, to the loss of a Brassica crop to clubroot. In total 65 crop trials were completed at 37 sites.

2.3.2. Trial Design and Management

Replicated N response plots were established at all sites. These comprised 6 rates of N, including a zero rate, in three randomised blocks. The overall size of the experiment was designed to minimise disruption to normal farming practice and was generally fitted within a half or full width of the on-site fertiliser spreader. Apart from fertiliser application and harvesting, the growers carried out all other crop husbandry according to farm (best commercial) practice. Where NPK compound was used by the grower in the remainder of the field, equivalent rates of P (as triple superphosphate) and K (as sulphate of potash) were applied by hand to the response plots. In the second year of a trial in the same field, trials were moved slightly so that subsequent trial plots were not affected by the management of the earlier trial. In two cases it was necessary to move the trial to a different field between seasons. These are indicated in Figure 2 as sites 3a & b and 6a & b.

Arable crops

In 1998, N application rates were selected to span the SUNDIAL predicted optimum application, with rates generally 15% and 30 % above and below. N was applied as ammonium nitrate by hand in one application (GS31 in cereals, before rapid stem elongation on oilseed rape and after emergence in potatoes and sugar beet). Following discussion of the results at a meeting of the farmers at IACR-Rothamsted in December 1998, trial designs for 1999 were modified slightly. The N rates used in the trial increased in regular increments from zero to a rate about 30% above the predicted optimum allowing response curves to be plotted more easily. Application of N was made in two applications in 1999: winter crops receiving a total N application greater than 100 kg N ha^{-1} had 50 kg N ha^{-1} applied by hand in February (GS30 in cereals). The remaining N was applied to each plot at the beginning of April (GS31/32 in cereals). Plots in cereals and oilseed rape ranged from 18 to 36 m^2 depending on the tramline width; smaller plots 5-12 m^2 were used in potatoes and sugar beet.

In 1998 some farmers also tested large unreplicated strips (often complete tramlines) of the SUNDIAL and WELL_N predicted optimum N application applied with farm machinery to compare to farm practice yields. However, few farms were able to maintain these trials through to the determination of final yields accurately. The most common problem was failure or inaccuracies of the yield meter on the combine. In 1999 separate estimates of farm practice yield were made at harvest on small hand-harvested plots.

Table 1. Site location and soil type.

Site Code	County	Soil Series	Topsoil Texture
1	East Yorkshire	Burlingham	Clay loam
2	Yorkshire	Escrick	Sandy clay loam
3	Kent	Hamble	Silt loam
4	Kent	Hamble	Silt loam
5	Bedfordshire	Bearsted	Sandy loam
6	Norfolk	Elmton	Clay loam
7	Lancashire	Downholland	Clay loam
8	Lancashire	Downholland	Clay loam
9	Shropshire	Hodnet	Sandy clay loam
10	Norfolk	Elmton	Clay loam
11	Hertfordshire	Hanslope	Clay
12	Hertfordshire	Hanslope	Clay
13	Cambridgeshire	Hanslope	Clay
14	Suffolk	Burlingham	Sandy clay loam
15	Suffolk	Burlingham	Sandy clay loam
16	Norfolk	Romney	Silt loam
17	Oxfordshire	Denchworth	Clay
18	West Sussex	Hook	Silty clay loam
19	Warwickshire	Bromsgrove	Sandy loam
20	Suffolk	Barrow	Sandy clay loam
21	Oxfordshire	Dullingham	Sandy clay loam
22	Suffolk	Swaffham Prior	Sandy loam
23	Lincolnshire	Wisbech	Silt loam
24	Lincolnshire	Tanvats	Silt loam
25	Norfolk	Newport	Loamy sand
26	Lancashire	Sollom	Loamy sand
27	Lancashire	Sollom	Humose loamy sand
28	Lancashire	Wisbech	Silt loam
29	Lancashire	Rufford	Sandy loam
30	South Yorkshire	Romney	Silt loam
31	Lincolnshire	Wisbech	Silt loam
32	Lincolnshire	Tanvats	Silt loam
33	Warwickshire	Wick	Sandy loam
34	Kent	Coombe	Silty clay loam
35	West Sussex	Hamble	Silt loam
36	Greater Manchester	Longmoss	Peat
37	Warwickshire	Whimple	Clay loam

Figure 1 Map showing location of trial sites

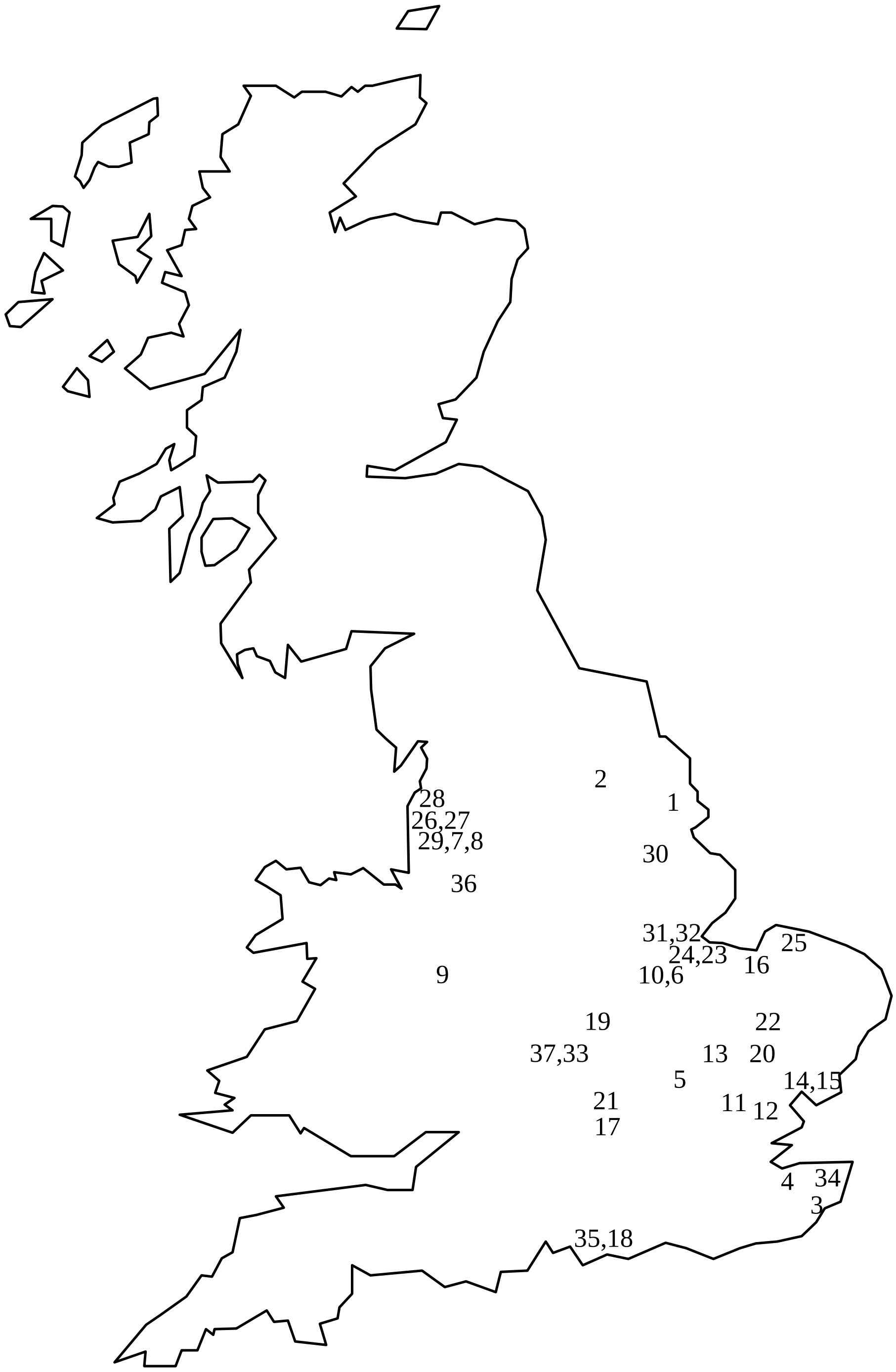
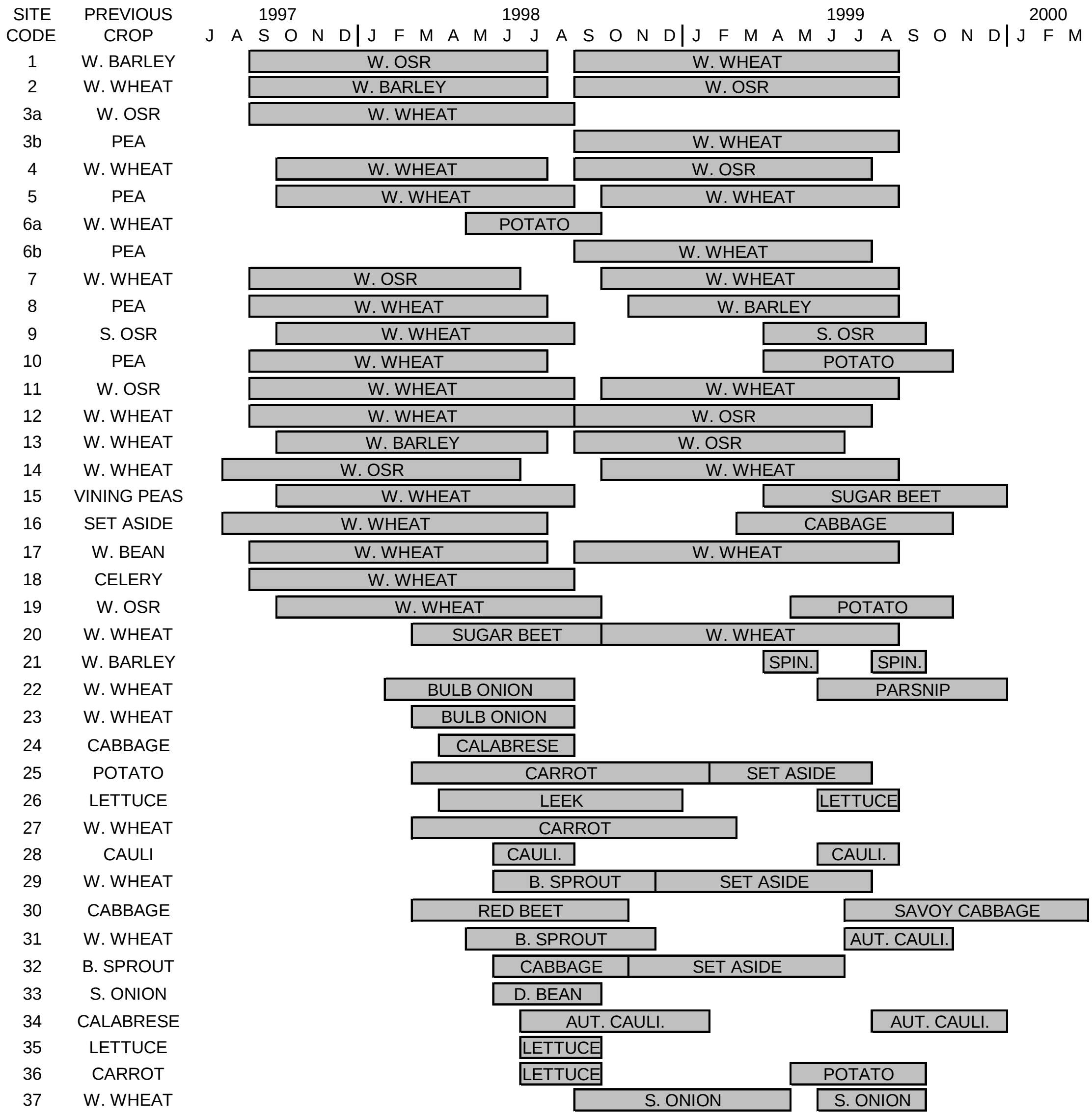


Figure 2. Trial crops at sites used for evaluation of fertiliser recommendation systems.



Crop abbreviations:

B. SPROUT	Brussel sprouts
CAULI	Cauliflower
D. BEAN	Dwarf bean
PEA	Field peas
S. ONION	Salad onion
S. OSR	Spring oilseed rape
SPIN	Spinach
W. BARLEY	Winter barley
W. BEAN	Winter field bean
W. OSR	Winter oilseed rape
W. WHEAT	Winter wheat

Horticultural crops

In both years the N rates were selected to span evenly between zero and the maximum used, as shown in Table 2, and included the WELL_N predicted optimum. Plot area varied between 7 and 40 m^2, depending on crop density and number of harvests. Nitrogen was applied by hand to each plot, as ammonium nitrate, or ammonium nitrate/ammonium sulphate mixture. At most sites, up to 75 or 100 kg N ha^{-1} was applied just before or just after drilling or planting, with any remainder applied after establishment. With the over-wintered salad onion crop (site 37 in 1998), the entire N was applied in the early spring. Where set-aside followed a vegetable crop (sites 25, 29 and 32 in 1999), no response trial was established but soil samples were taken (section 2.3.3).

Table 2. Horticultural sites – N application rates

Site code	Year	Crop	Response trial N applied[1] kg/ha				
21	1999a	Spinach	50	100	150	200	250
21	1999b	Spinach	50	100	150	200	250
22	1998	Onion	40	80	115	165	215
22	1999	Parsnip	40	80	120	160	200
23	1998	Onion	50	90	125	175	225
24	1998	Calabrese	50	100	150	200	275
25	1998	Carrot	25	50	75	100	125
26	1998	Leek	50	100	175	275	375
26	1999	Lettuce	50	100	150	200	250
27	1998	Carrot	25	50	75	100	125
28	1998	Cauliflower	75	150	225	300	375
28	1999	Cauliflower	75	150	225	300	375
29	1998	Brussels sprout	125	200	275	350	425
30	1998	Red beet	50	100	150	200	250
30	1999	Savoy cabbage	100	175	250	325	400
31	1998	Brussels sprout	100	175	250	325	400
31	1999	Autumn cauliflower	70	140	210	280	350
32	1998	Dutch white cabbage	50	125	200	275	350
33	1998	Dwarf bean	50	100	150	200	250
34	1998	Autumn cauliflower	75	150	225	300	375
34	1999	Autumn cauliflower	50	100	150	225	300
35	1998	Lettuce	75	125	175	225	275
36	1998	Lettuce	50	100	150	200	250
36	1999	Potato	50	100	150	200	250
37	1998	Salad onion	40	80	120	160	200
37	1999	Salad onion	40	80	120	160	200

[1] All experiments include a zero N treatment

Most growers were keen on locating a large, unreplicated area alongside the response plots on which the WELL_N rate of N would be spread using farm equipment, for comparison of yield with their normal field rates. As with the arable trials, this proved difficult to achieve in practice. In 1998 at several sites, N could not be varied independently of P and K as the grower applied the base application of N as a compound. At others, either no top dressing was planned or it was too wet to apply it, or model and farm rates were within 25 kg N ha^{-1} of each other or the plots were lost through application errors. Five sites were established in 1998. One of these (onion, site 22) was discarded because of soil variability, one (carrot, site 27) because of a lack of response to N and one (leek, uncoded) because of a harvesting error, leaving just two sites, leek (site 26) and red beet (site 30). This approach was not therefore pursued in 1999.

It was planned to monitor the grower application rate of granular N at as many sites as possible using IMATS (Independent Machinery Advisory & Technical Services) catch trays placed across the width of the spreader bout. Timing of site visits to coincide with applications proved difficult to organise and was achieved at only three sites. At two of these, which were using a single disc spreader, the measured rate was either 40% less or 50% more than the target. At the other site the rate, using a twin disc broadcaster and double overlap spreading, was within 15% of the desired amount. This suggests that growers need to ensure that they are getting the best from their machinery in order to maximise the benefits from sophisticated recommendation systems.

2.3.3. Soil and Crop Sampling

In spring, soil mineral N was measured on the response plots before fertiliser was applied. Six cores per block were bulked in increments of 30 cm to a depth of 90 cm or to rock. Between crop harvest and post-harvest cultivations, topsoil samples (0-30 cm) were taken in each plot of the N response trial with six cores taken per plot. In addition cores were taken to a depth of 90 cm (in increments of 30 cm) in plots which had received no N fertiliser and in the plots with the largest N application. Core samples were taken at each sampling to measure the topsoil bulk density.

All the plot trials in arable crops were harvested ahead of the farm fields, usually in the week immediately preceding combining. At harvest the central strip of each plot was cut using an Allen scythe for oilseed rape and cereal crops allowing the recovery of both grain and straw samples. On average a yield area of 8 m^2 was cut in each plot. The total biomass was weighed in the field and a sub-sample brought back for processing. Oilseed rape was cut just before the main crop was swathed and allowed to mature at Rothamsted to minimise seed loss. Cereals and oilseeds were threshed and sub-samples of grain, chaff and straw kept for analysis. Potatoes and sugar beet were lifted by hand from a minimum length of 2 m of paired yield rows. For all the potato crops sampled, the tops had been desiccated before sampling. However, for sugar beet the whole crop was sampled. Beet and tops were separated, washed and weighed, and a sub-sample kept for analysis. Potatoes were graded by size and a sub-sample of the ware grades was kept for analysis.

In the horticultural trials, yields were assessed from a minimum harvest area of 2 m of bed length (close-row crops) or 30 plants (wide-spaced Brassicae) on each response plot. All trials were hand harvested and timed to coincide closely with the commercial harvest, although we were required to clear one lettuce trial (site 35) a week early when the crop was slightly immature. In line with commercial practice, summer and early autumn cauliflower and calabrese were cut over on three occasions. Maturity of the late autumn cauliflower, grown on the Isle of Thanet (site 34), was delayed by low autumn temperatures and due to the risk of frost damage, in contrast to the commercial crop, were harvested as a single cut. Late maincrop carrots were lifted prior to strawing in October when the foliage was still present and also following dieback during the commercial harvest period. Total, marketable and residue fresh and dry weights were recorded for all crops. Where applicable, assessments of quality and size grading were made, as listed in Table 3, in order to provide data on the relationship between these parameters and N application rate.

Table 3. Horticultural sites - measured yield parameters

• All crops	Total, marketable and residue fresh and dry weights Plant population and % dry matter
• Brussels sprout	Size grades: 10-25, 25-30, 30-35, 35-40 mm
• Bulb onion	Size grades: <40, 40-50, 50-60, 60-80 and >80 mm
• Cabbage	Individual head weights
• Calabrese	Individual head weights and diameters
• Carrot	Size grades: <20, 20-25, 25-30, 30-35, 35-40, 40-55 mm and misshapen
• Cauliflower	Individual curd weights, diameters, quality class and defects
• Leek	Size grades: <15, 15-50, >50 mm
• Lettuce	Individual head weights and iceberg quality heads
• Parsnip	Size grades: <30, 30-35, 35-65, 65-75, 75-130 mm and misshapen
• Potato	Size grades: 25-45, 45-65, 65-85, >85 mm and outgrades
• Red beet	Size grades: <25, 25-45, 45-65, 65-75, > 75 mm and misshapen
• Salad onion	Size grades: <8, 8-18, >18 mm

2.3.4. Sample Analysis
Soil samples were sieved to remove stones and stored for no longer than one week at 4ºC before extraction. Where a delay was unavoidable, the soils were stored frozen. Soil mineral-N (nitrate plus ammonium-N extracted with saturated potassium sulphate solution) was measured by HPLC and colorimetry, respectively. Topsoil samples were also characterised for bicarbonate extractable P, ammonium nitrate extractable K, pH and total N (MAFF, 1986)

Crop samples were dried at 100°C and milled to fine flour before measuring total N content by thermal conductivity using a LECO® CN2000 combustion analyser.

2.3.5. Statistical Methods
Analysis of variance was used to test for significant effects of N application. The yield response to applied N was examined and described by a 'linear plus exponential function' (George, 1984), where appropriate:

$$Yield = a + br^N + cN$$

where N is the total amount of N applied (kg ha^{-1}); a, b, and c are linear coefficients and r is a non-linear parameter. Genstat was used for preliminary curve fitting with floating r.

The economic optimum N application was defined for all crops as the N application rate after which a 1 kg increase in N applied increased marketable yield by less than 1%, and was identified from the gradient of the fitted relationship. This is not the same definition of economic optimum commonly used (eg. Sylvester–Bradley *et al.*, 1984), but allows one method to be used for all crops, including vegetables, whose price can fluctuate widely and are dependent on quality. After preliminary curve fitting in Genstat, data were imported into MLP, which was used to estimate the optimum and the precision of this estimate. The parameters of the linear plus exponential model were usually highly correlated and their dispersion matrix was often nearly singular. Therefore, except where the optimum was fairly well determined with data values falling away clearly on either side, it was difficult to assign a standard error to the estimate of the optimum. Confidence limits were usually very skew and possibly unlimited at the upper end. The lower 95% confidence limit was therefore used to give an indication of the precision of the estimate of the optimum.

Yields were calculated for all the recommended rates, from the linear plus exponential curve fitted to the trial data. In trials where there was no significant response to applied N, the optimum was taken as zero and the yield at optimum as the mean trial yield.

2.4. Evaluation of Decision Support System

WELL_N and SUNDIAL-FRS were used independently to predict the optimum N application for each crop. The simulations were carried out separately for the first year crops, with the second crop run in rotation with the first year farm crop. The data used was extracted from the database of field trials.

The WELL_N model is the same version as that included within the commercially used HRI MORPH decision support system (Draycott *et al*, 1999). However, within the project the model was extended to allow it to be run rotationally. For crisp lettuce, the parameter WLRT (the dry weight in t ha $^{-1}$ when roots reach the mid-point between rows), was updated to take account of recent work with glasshouse lettuce (Burns *et al*, 2001). WELL_N was run automatically within the database system using specially prepared procedures (Section 3.2). As in MORPH, estimates of the optimum were made to the nearest 25 kg N ha^{-1}. WELL_N predictions were not made for sites receiving large amounts of organic manures, or for oilseed rape for which crop parameters are not included in the currently available version. Two other trial crops, savoy cabbage and salad onion are not specifically parameterised in WELL_N but were run as Dutch white cabbage and bulb onion respectively, albeit with a lower yield. Default values for soil mineralisation rates (0.70 kg N ha^{-1} day^{-1} at 15.9°C) were used for all soils apart from peat (site 36). WELL_N has not previously been used on peat soils due to uncertainties in mineralisation rates. Opportunity was therefore taken to estimate mineralisation rate at the peat site from the measured changes in spring and post harvest soil mineral N and plant N uptake on the zero N plots. Since these mineralisation values were not independent of the field data, however, the simulations from the peat site were not used in the evaluation of the model.

The SUNDIAL-FRS recommendations and simulations were run with SUNDIAL-FRS V3.0. SUNDIAL-FRS was run separately to the database system after extracting the data for set-up files. Sites were run with as much previous cropping information as was available, up to 5 years for some sites. Recommendations were obtained for all the arable crops (sites 1-20) but not all the horticultural crops. No recommendations were derived for spinach (Site 21), parsnip (Site 22/99), calabrese (Site 24/98), lettuce (Sites 26/99 and 35/98), red beet (Site 30/98) or dwarf bean (Site 33/98) as SUNDIAL is not parameterised for these crops. Neither was it possible to run simulations for the peat soil (Site 36), as SUNDIAL is not parameterised for organic soils. SUNDIAL is not specifically parameterised for salad onion (Site 37), so it was run as bulb onion, with adjustments for the different dry matter contents, as this in physiologically very similar.

The initial SUNDIAL recommendations and simulations for **cauliflower** were very poor. The crop was often unable to take up the full N requirement, resulting in very low calculated yields and recommendations. The parameters were modified, with much improved results. The presented recommendations are for the new parameters, but the results are not used in the final evaluation of the SUNDIAL recommendations.

For each model, an initial, **predictive** optimum was obtained. This was based on grower estimates of potential marketable yield, using actual weather (obtained from the nearest Meteorological Office site) prior to the first N application and default weather for the remainder of the season. WELL_N also included the spring SMN measurements where available. To compare the effect of default and actual weather at the same potential yield, a second WELL_N predictive recommendation used actual weather for the whole season. A second SUNDIAL predictive recommendation was carried out, which included spring SMN measurements as diagnostics.

A **retrospective** optimum was subsequently obtained using actual weather for the whole of the season and 'actual' yields. WELL_N used the maximum total dry weight yield from the trial, SUNDIAL-FRS used the calculated marketable yield at the optimum N rate. The SUNDIAL retrospective recommendation was obtained both with and without the use of spring SMN measurements. . These predictions were compared with the optimum N application determined from the field trials (Section 2.3.5).

Retrospective simulations of the response trial plots (where no N had been applied and at the highest rate) were also carried out with each model to predict the mineral N remaining in the soil at harvest and crop N uptake. SUNDIAL also provided a retrospective simulation at the farm rate for the arable sites. The simulations used the actual weather, crop yields and N application rates, and spring SMN values, if available. These predictions were compared with the replicate measurements made in the field trials.

Measurements and simulated values were compared using the statistical methods outlined by Smith *et al*. (1997), across all sites and using groups of crop or soil types where at least 8 comparisons were possible.

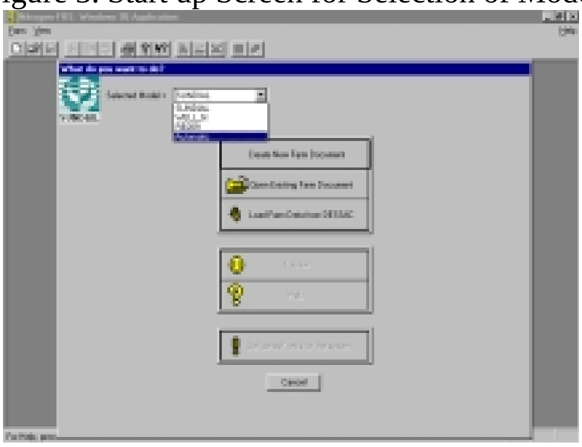
3. Results and Discussion

3.1. Decision Support System

3.1.1. Selection of Model

The selection of models can be either manual or automatic. On entering the system, a *Start Up Screen* is displayed, that allows the user to select the model and choose the source of input data (Figure 3).

Figure 3. Start up Screen for Selection of Model and Source of Input Data



If automatic model selection is chosen, the system will select the most appropriate model, based on the results of the model evaluation completed for this project.

The models currently available in the system are SUNDIAL, WELL_N and the MAFF Reference Book 209 (1994). On manually selecting the model, the model *Title Screen* is displayed and the icon in the top left corner of the screen changes to indicate the new model selection. The title screens for SUNDIAL and WELL_N are shown in Figure 4.

Figure 4a. Title Screen for SUNDIAL

Figure 4b. Title Screen for WELL_N

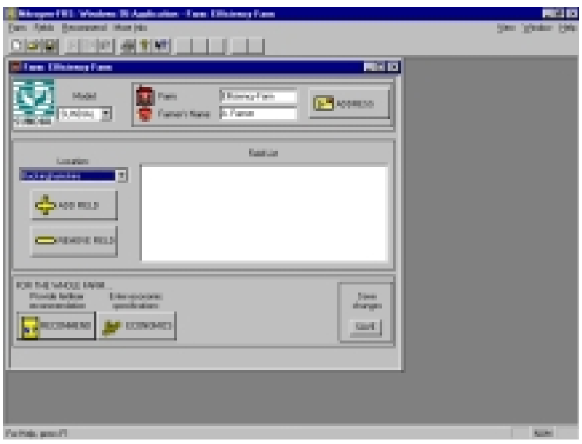
The model *Title Screen* acknowledges sponsorship by the project partners, the organisations responsible for the development of the model and the contributions from individual researchers. The icon associated with the selected model is given in the top left corner of all the main windows and a drop-down list is provided to allow the model selection to be easily changed at any stage.

3.1.2. Input of Data

The input screens are equivalent for all models. This is essential if the system is to move seamlessly between models.

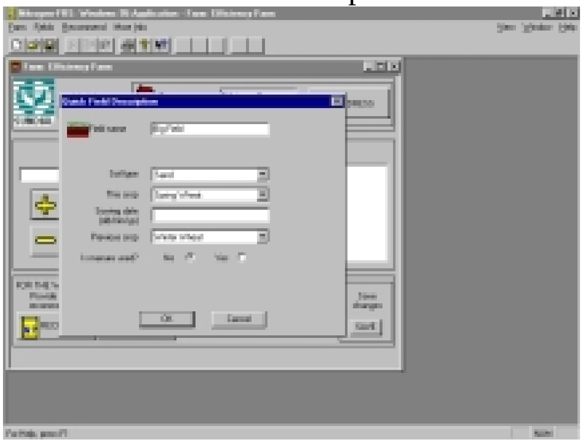
The first data input screen displayed is the *Farm Screen* (Figure 5). This screen displays the farm identity, and contains controls that allow the user to change the address, location, and economic settings, and to add and remove fields. The location of the farm is selected from a drop-down menu. This information is used to select default values and the statistics selected to run the weather generator.

Figure 5. Farm Screen, Showing Selection of Farm Location



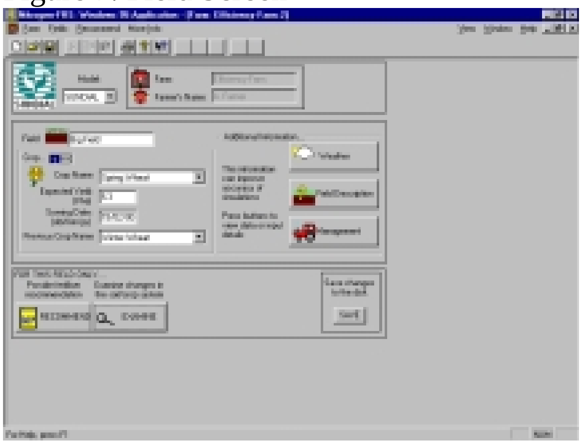
On pressing the *Add Field* button, a *Quick Field Screen* is displayed to allow the user to obtain a default description of the field with minimum requirement for input data. Here the soil type, current crop, sowing date, previous crop and manure use may be specified (Figure 6). Missing values are filled in by an underlying database of regional defaults. Selecting OK takes the user to the field screen with all data input controls completed. Clearly, a more accurate recommendation will be obtained if more field specific data is entered. Upon running the simulation, the user is provided with a screen detailing the default values used.

Figure 6 Quick Field Description Screen used by SUNDIAL and WELL_N to define field data with minimum user input

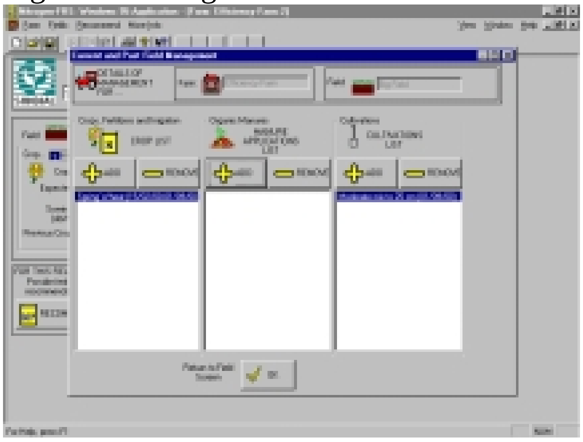


The *Field Screen* summarises the entered data. It also includes buttons that allow more field specific information to be entered and model simulations to be run (Figure 7).

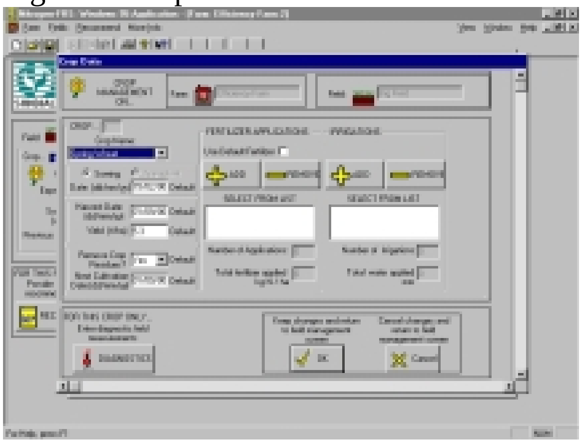
Figure 7. Field Screen



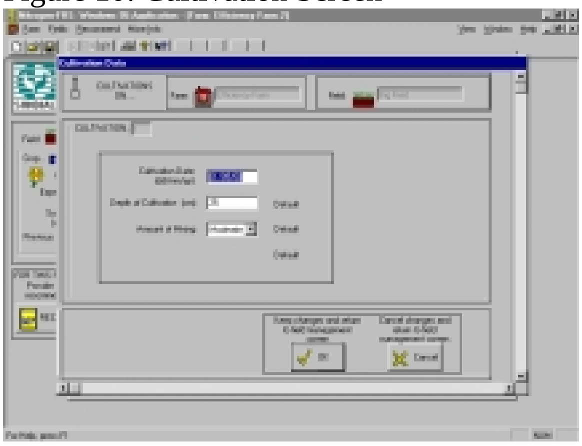
Selecting the *Management Button* (Figure 8) brings up lists of the crops, manure applications and cultivations already specified in the field management. From this screen, cropping, manure and cultivation details can be viewed, added or removed.

Figure 8: Management Screen


Selecting to add or view crop data brings up the *Crop Screen* (Figure 9). From this screen details crop management, fertiliser applications and irrigations can be added. In addition, diagnostic field measurements can be included that will be used by the models to modify the simulations.

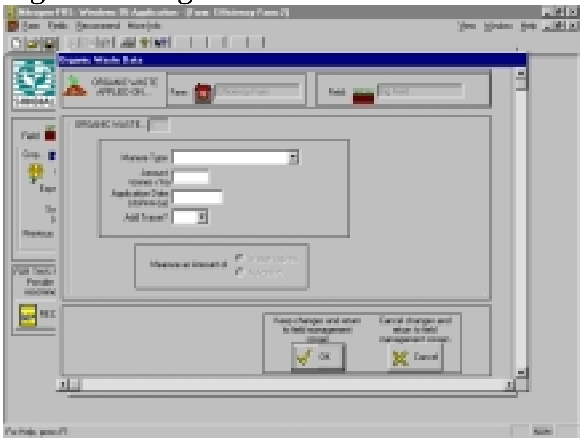
Figure 9. Crop Screen


Similarly, selecting to add or view cultivations brings up the *Cultivation Screen* shown in Figure 10.

Figure 10: Cultivation Screen


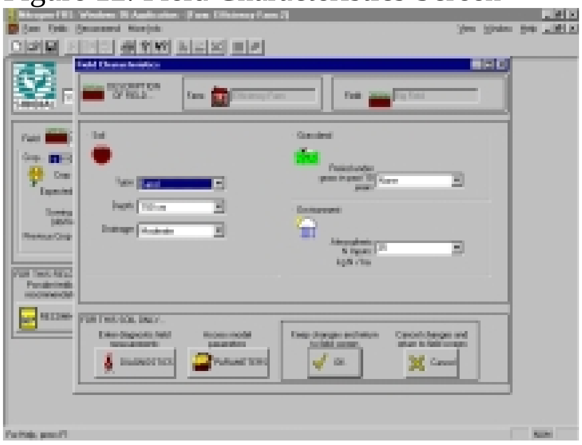
Selecting to add or view organic waste brings up the *Organic Waste Screen* (Figure 11). Application of organic waste is not included in WELL_N.

Figure 11: Organic Waste Screen



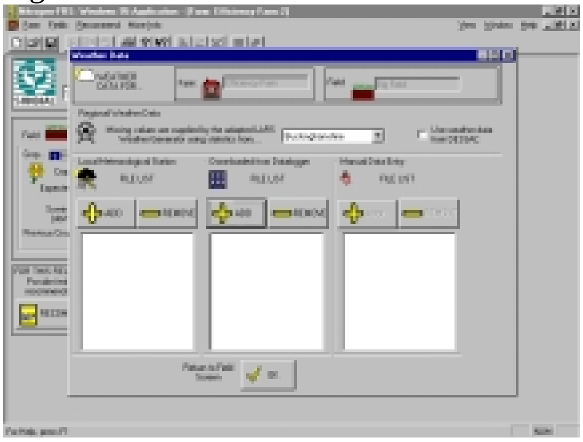
Selecting the *Field Description Button* from the *Field Screen* (Figure 7) brings up the *Field Characteristics Screen* (Figure 12) which displays and allows the user to make changes to the soil type, depth, drainage, period under grass in the past 10 years and atmospheric N inputs. The screen also includes two buttons: the *Diagnostics Button* and the *Parameters Button*. The *Diagnostics Button* allows diagnostic field measurements to be entered to improve the site specificity of the model simulations. The *Parameters Button* allows the user to view and change soil parameters, and to create new soil types for future use.

Figure 12. Field Characteristics Screen



Selecting the *Weather Button* from the *Field Screen* (Figure 7) brings up the *Weather Screen* (Figure 13). From here, weather data can be loaded from a local meteorological station, downloaded from a datalogging meteorological station on the farm, or entered manually.

Figure 13. Weather Screen



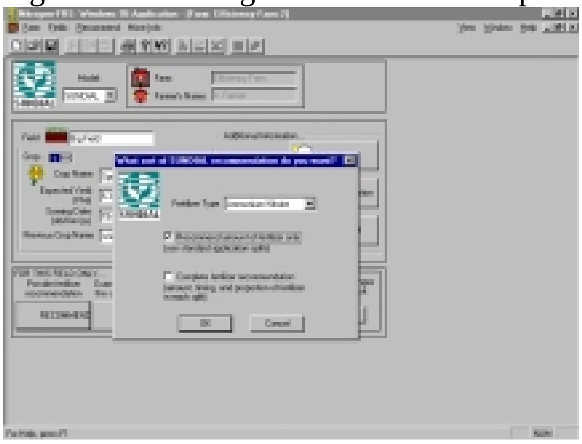
3.1.3. Calculation of Fertiliser Recommendation

The *Recommend Button* on the *Field Screen* (Figure 7) tells the system to run the selected model to provide a fertiliser recommendation. Whereas the input screens are equivalent for all models in the system, the screens associated with running simulations are necessarily different, because mode of operation and results from the models are different. Because the data used by each model is also different, the portion of the entered data that has been used in the simulation is echoed back to the user, indicating whether the information is derived from default values or user input.

SUNDIAL

The system allows the user to select *partial* or *full* optimisation for SUNDIAL (Figure 14). A partial optimisation includes only optimisation of the total amount of fertiliser applied. The full optimisation includes optimisation of all factors (i.e. amount, timing, number of splits and proportion in each split).

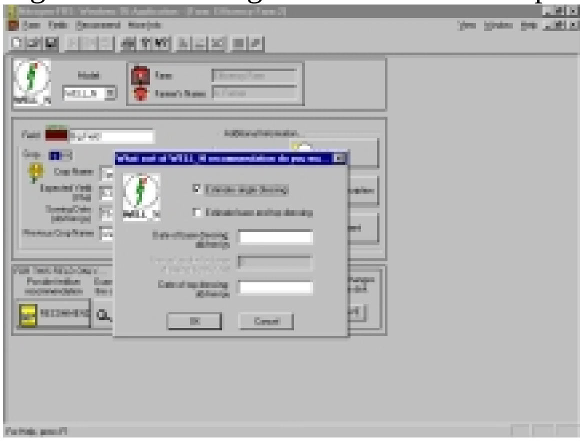
Figure 14: Selecting Mode of Fertiliser Optimisation for SUNDIAL



The fertiliser recommendation is calculated using a grid search that is initiated at the application rate given in MAFF reference book 209 (1994) and capped at a rate that achieves the required crop N offtake.

WELL_N
The system allows 2 modes of optimisation for WELL_N: estimate a single dressing only; or estimate base and top dressing (Figure 15). The dates of the fertiliser applications must be specified by the user. Before estimation of a single dressing, any previous applied dressings must be specified.

Figure 15: Selecting Mode of Fertiliser Optimisation for WELL_N



RB209
MAFF Reference Book 209 (1994) is included in the system, and provides recommendations via a series of look-up tables and rules within the computer code. No optimisation is possible for RB209.

3.1.4. Presentation of Results

Fertiliser Recommendations
Recommendations can either be presented for a single field (Figure 16) or for the whole farm (Figure 17). Applications listed in the whole farm recommendation can be sorted either in date or field order, depending on user preference.

Figure 16: Field Fertiliser Recommendations

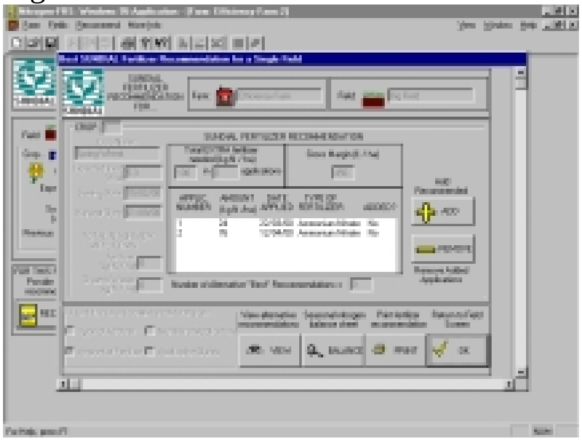
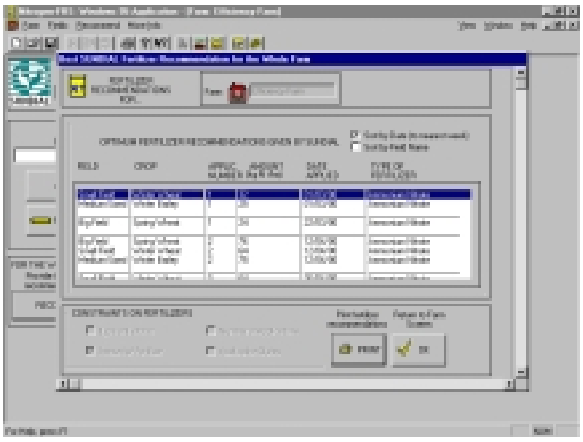


Figure 17: Farm Fertiliser Recommendations



A third type of recommendation screen, displaying the changes as the optimisation proceeds in the fresh weight, dry weight, crop N, soil mineral N and N leaching is currently under consideration

Examine Results

The *Examine Button* on the *Field Screen* allows the user to view balance sheets, graphical plots and flow diagrams displaying the simulated changes in N over time (Figures 18, 19 and 20).

Figure 18. Seasonal N Balance Sheet

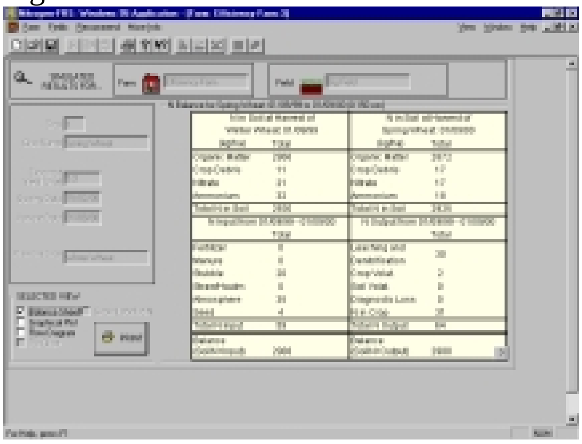


Figure 19. Graphical Plot of Changes in N throughout the Period of the Simulation

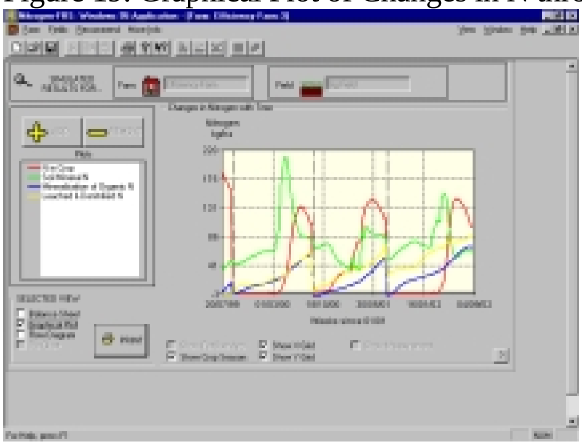
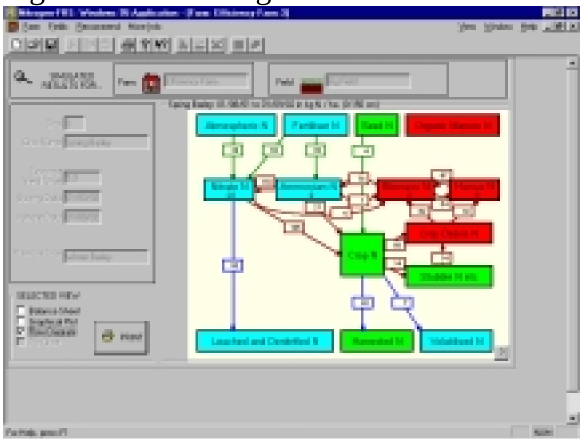


Figure 20. Flow Diagram of Seasonal N Fluxes



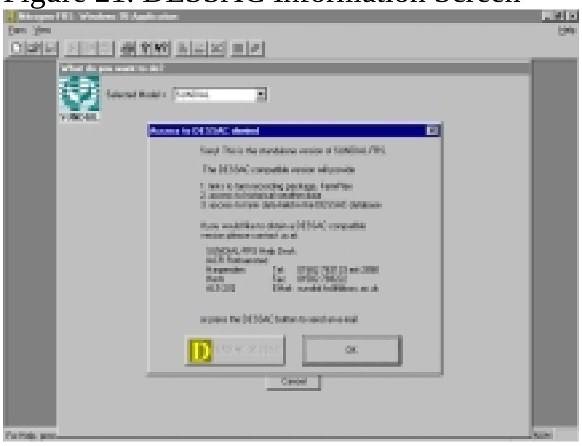
Detailed results are also output in ASCII files so that the more experienced user can analyse the results in any standard spreadsheet software.

3.1.5. DESSAC Compatibility

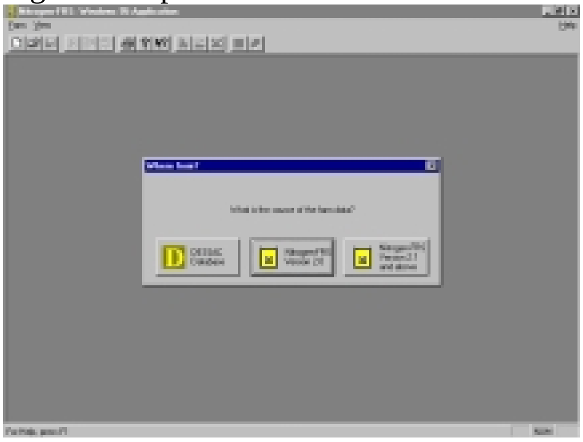
A DESSAC compatible version of the system is currently being developed under other funding (MAFF NT2306). It is envisaged that the system will be available both as a standalone and a DESSAC compatible version. This is essential if the system is to be accessible to DESSAC and non-DESSAC users alike. Buttons and screens have been included in the system to ensure that the user of the standalone version is fully aware of the additional functionality of the DESSAC compatible version.

On entry to the system, the *Startup Screen* (Figure 3) includes a button to *Load Farm Data from DESSAC*. In the standalone version, selecting this button will bring up the *DESSAC Information Screen* (Figure 21). This informs the user that farm data cannot be loaded directly from DESSAC in the standalone version.

Figure 21. DESSAC Information Screen

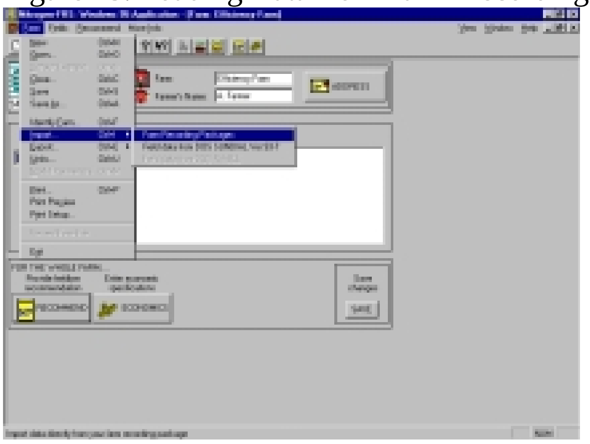


On selecting the *Open Existing Farm Document Button* in the *Startup Screen* (Figure 3), the user is asked to specify the source of the data (Figure 22).

Figure 22. Specification of Data Source


On selecting the *DESSAC database Button* from the standalone version, the DESSAC Information Screen (Figure 21) is displayed to inform the user that the standalone version includes no direct access to the DESSAC database.

In the *Nitrogen-FRS Application Screen*, selection of the menu item *Farm – Import – Farm Recording Packages* (Figure 23) brings up the *DESSAC Information Screen* to inform the user that access to farm recording packages is only available via DESSAC.

Figure 23. Loading Data from Farm Recording Packages


The *Weather Screen* (Figure 13) includes a check box to select historical weather data from the DESSAC database. In the standalone version this is initially unchecked. If user selects this option, the *DESSAC Information Screen* (Figure 21) is displayed to inform the user that historical weather files from DESSAC are unavailable in the standalone version. Historical weather data must therefore be obtained either by the user from a datalogging meteorological station on the farm or the nearest meteorological office site, or automatically through the internal weather generator.

3.1.6. Continuing Development
Because users testing the interface are still providing suggestions for improvements, the layout of the system continues to develop. The above description relates to the status of Nitrogen-FRS, Version 2.1, on 21st July 2000.

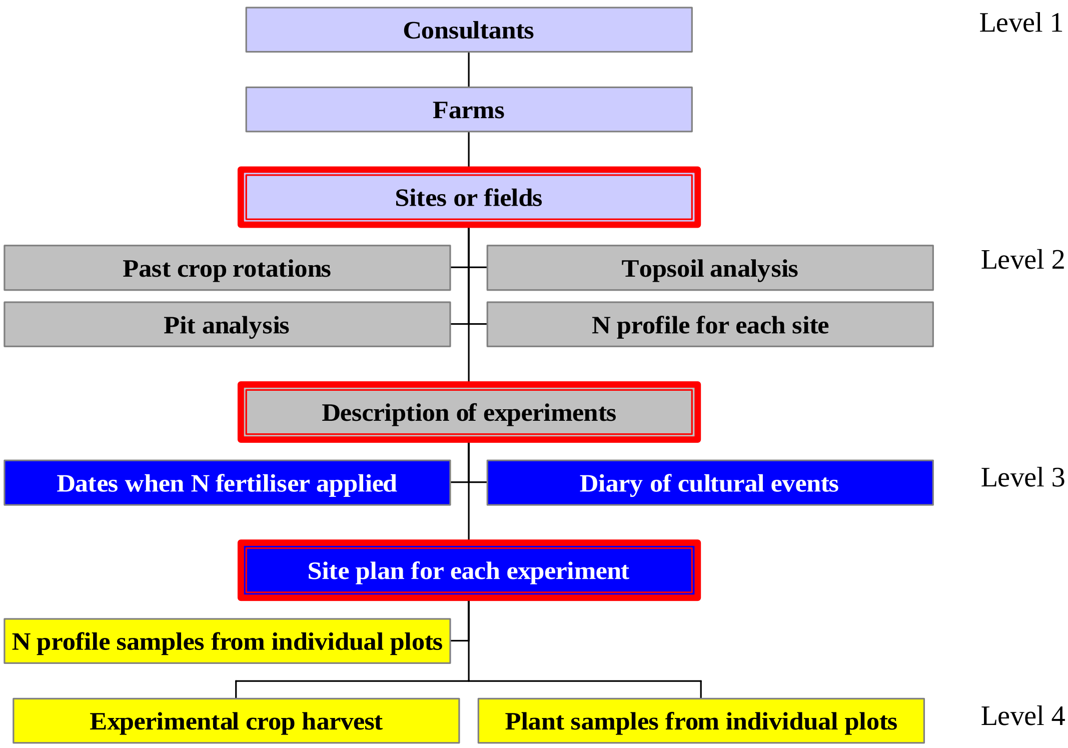
3.2. Database of Field Trials

The database has been designed with the flexibility to store all of the data from the field trials within a single structure. This has been achieved by storing the data within a hierarchical structure, starting with site identifiers (name of farmer etc.) expanding to general site data (e.g. location, soil type and previous husbandry details), and further to incorporate data from each crop and finally to data collected from each experimental plot:

- General data (Level 1) contains site identifiers.
- Site (Level 2) contains soil description and cultural history.
- Experiment (Level 3) contains details for each crop in rotation.
- Plot (Level 4) contains data recorded from individual plots.

Figure 24 below shows the four different levels each in a different colour. Tables which provide the link to the lower level are denoted by a red border.

Figure 24. Diagram showing hierarchical structure of data storage tables within the database.



The datafields are grouped into tables linked into the overall hierarchical structure, as shown below in Figures 25(a-d). This allows the relationships, which exist between the different tables to be recognised and used both during data entry and subsequent extractions. In addition to the main experimental data tables, memo tables have been included for supplementary unstructured information. These memo tables have been provided within hierarchical levels 2 to 4.

Figure 25(a). Relationships between Tables in the Database: Levels 1 and 2 (General Site Data).

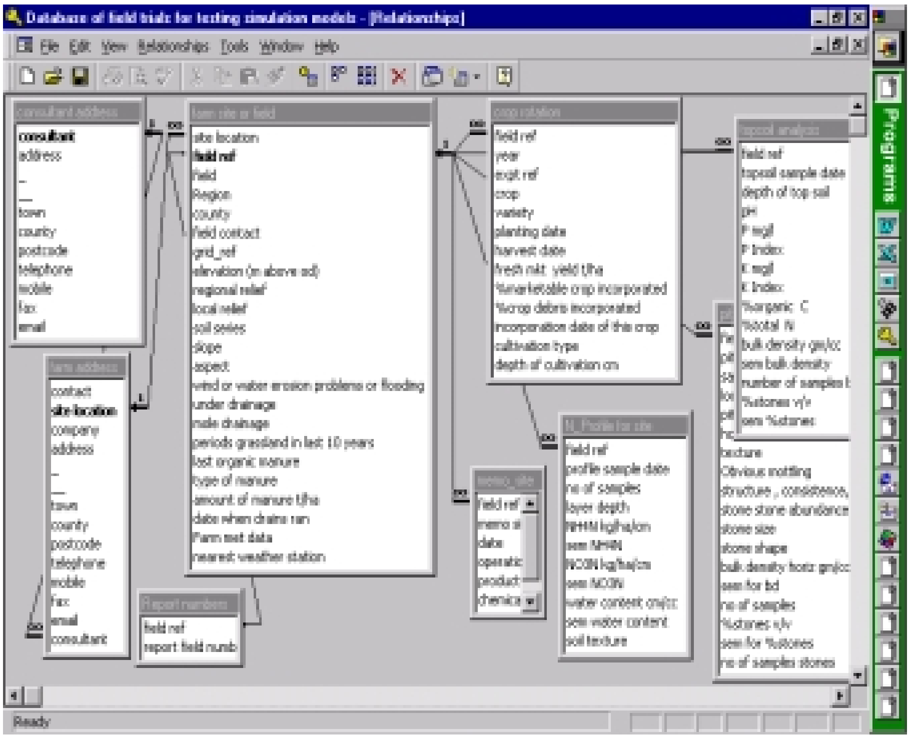


Figure 25(b). Relationships between Tables in the Database: Level 3 (Data from each crop in rotation).

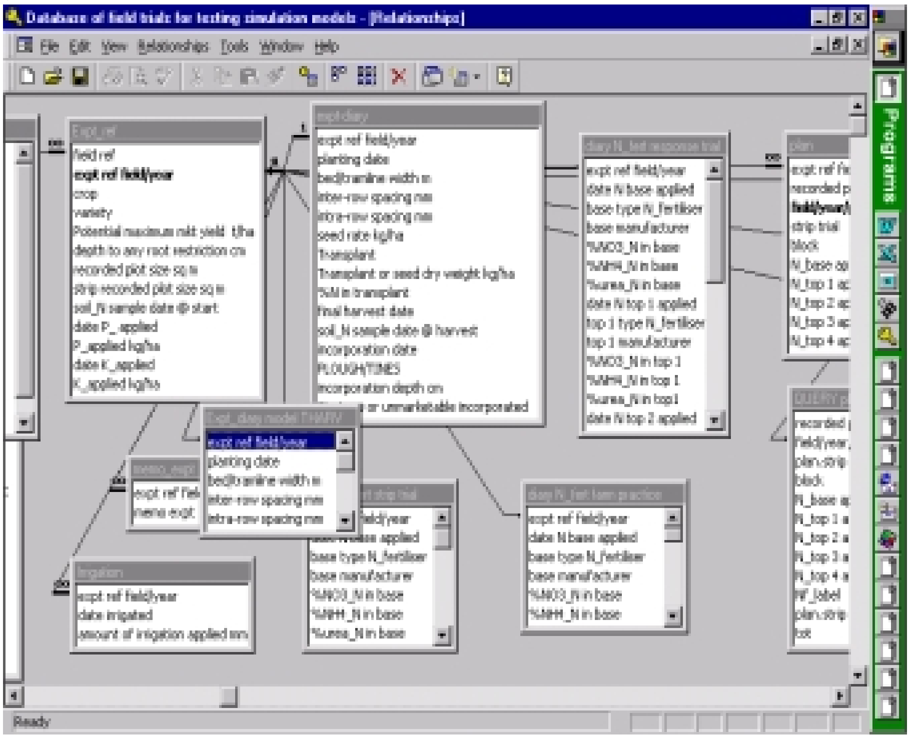


Figure 25(c). Relationships between Tables in the Database: Level 4 (Individual Plot Data).

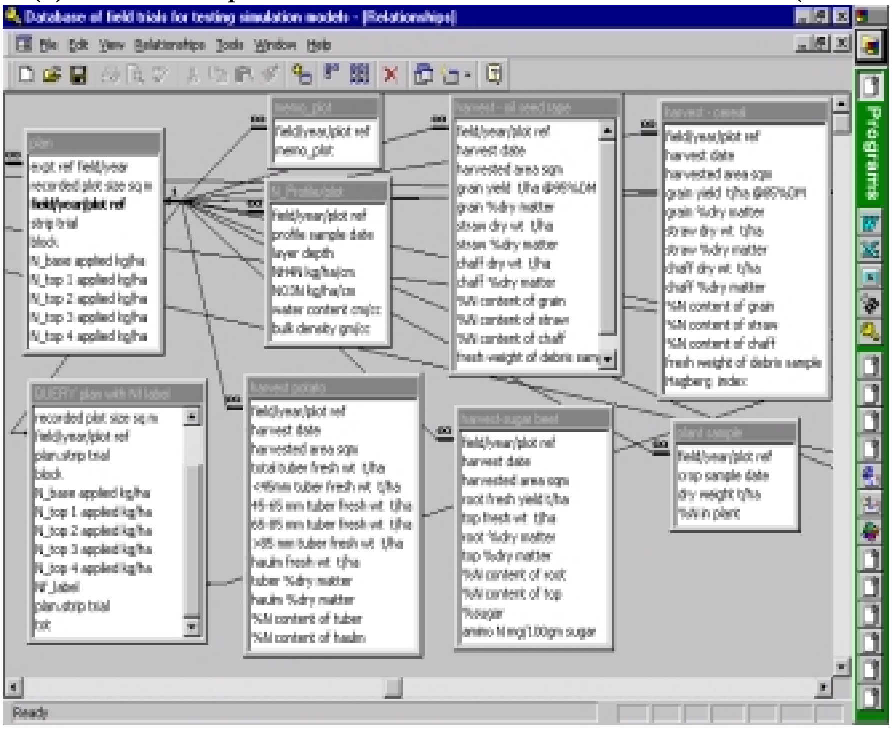
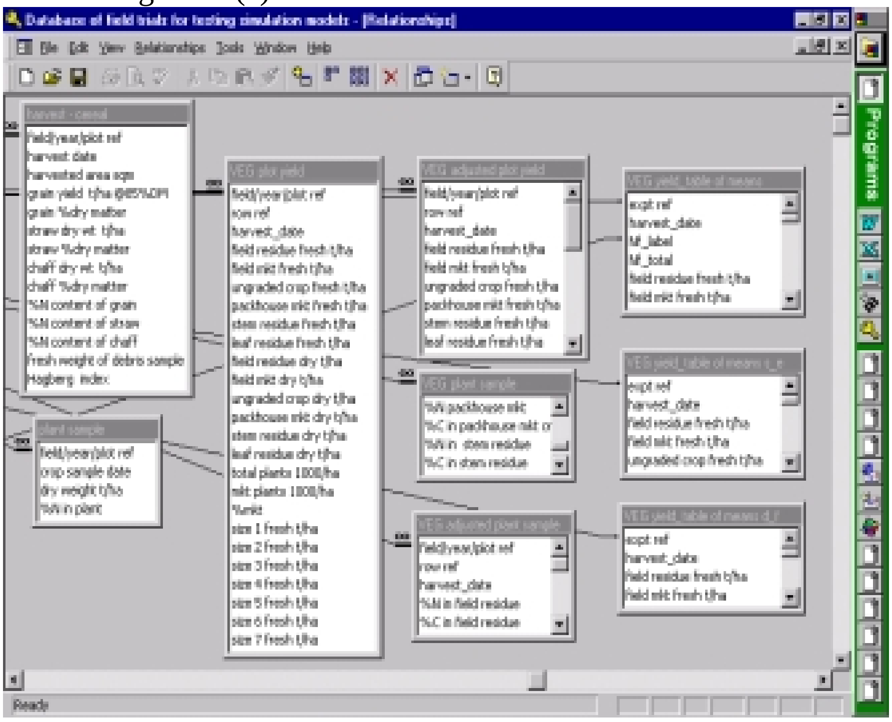
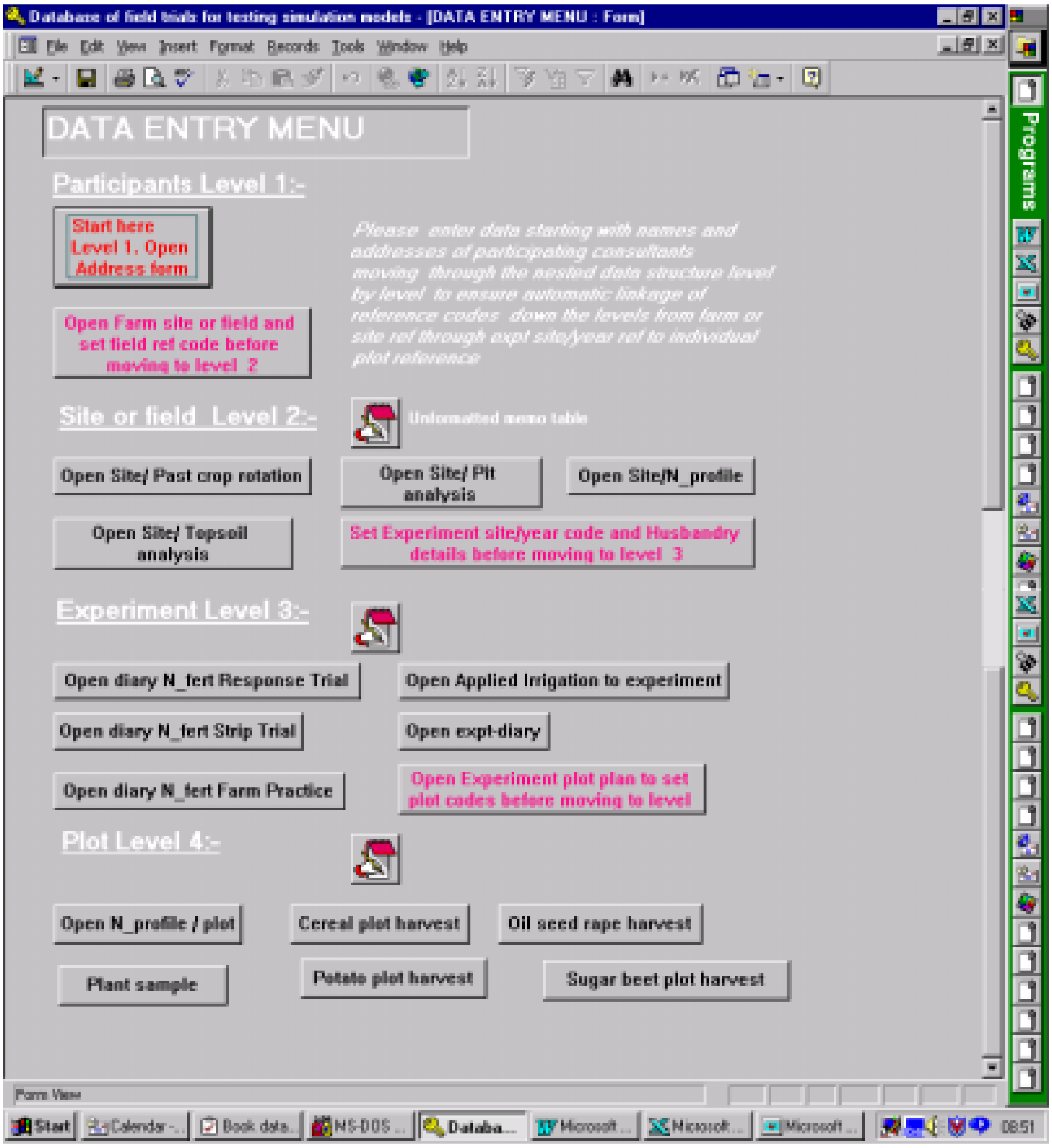


Figure 25(d). Relationships between Tables in the Database: Level 4 (Individual Plot Data) continued from Figure 25(c).



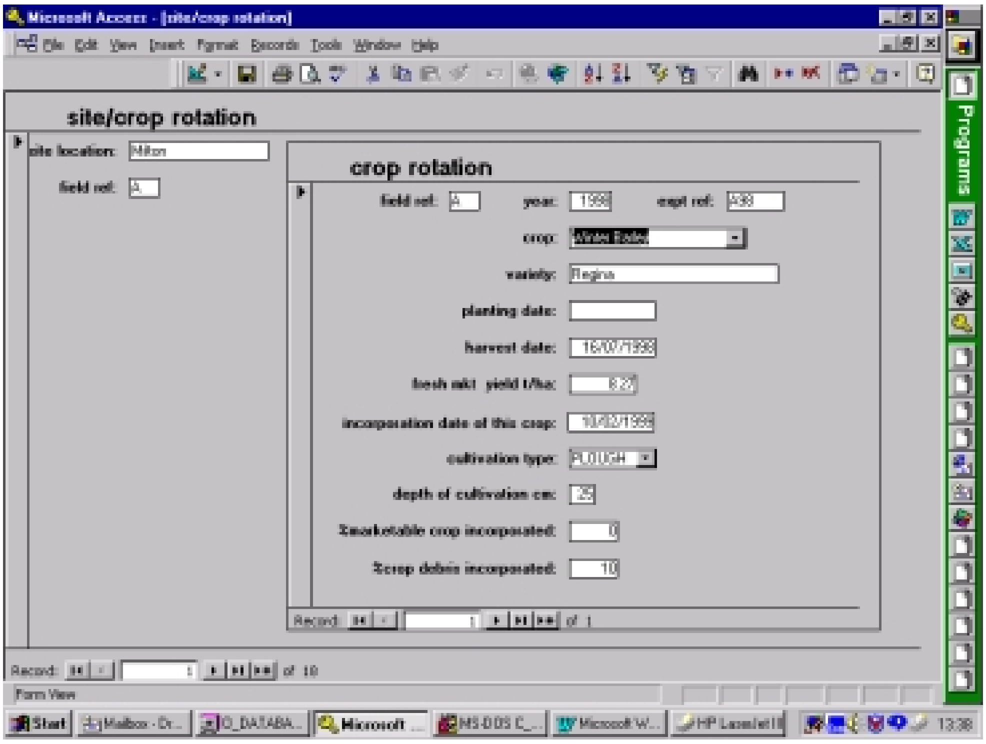
A push button menu shown in Figure 26 guides the user through the nested data entry forms provided for each table. Memo tables are provided at each level as described above. Pre-prepared data input forms were provided for the arable crops where the number of recorded data items at harvest was manageable. However, because of the diverse nature of the vegetable crop data, prepared input forms were not provided for these crops. Instead, the data was assembled in Excel Spreadsheets and pasted directly into the harvest tables.

Figure 26. Data Entry Menu.



One example of the prepared input forms is given in Figure 27. This shows data from two data tables displayed on a single input form. The field ref, entered with farm site or field description is linked through into the crop rotation table as a result of the relationship defined between the tables.

Figure 27. Example of an input form.



The database opens with sequenced title screens as shown in Figure 28. Command buttons direct the user to other screens such as that in Figure 29, which controls pre-defined data extraction procedures.

Figure 28. Database opening title screens.

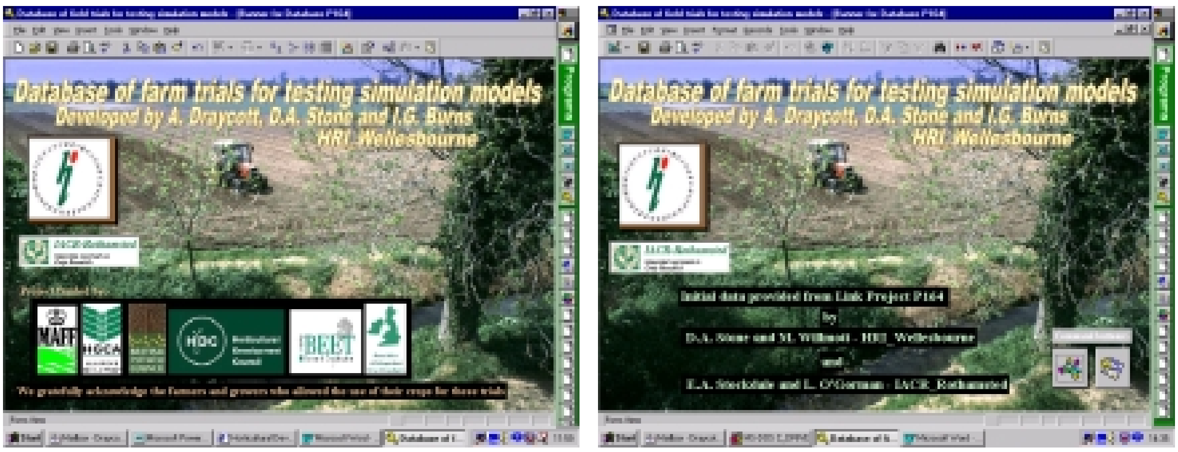
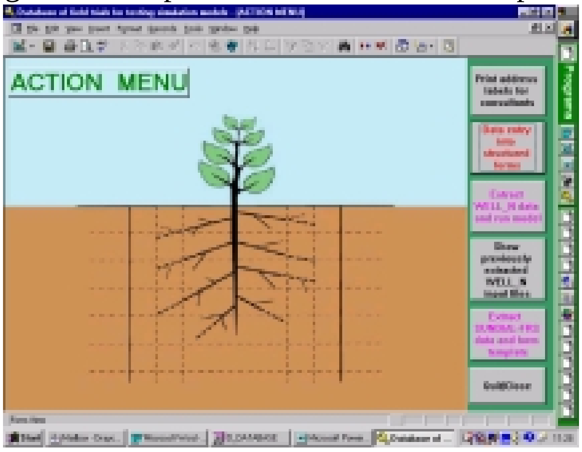


Figure 29. Controlling screen for pre-defined data extraction procedures.



Automatic data extraction for model testing was achieved by the use of procedures, specially written for this project. The system automatically extracts data from the database and formats it to enable the WELL_N and SUNDIAL-FRS models to be run rotationally for a selected site. Using queries, data is gathered together from the different storage tables to produce reports, which are exported to DOS text files. These files are automatically assembled by specialised utilities into input files for the simulation models. The operation is controlled by specialised Visual Basic for Applications (VBA) procedures within both modules and forms, together with DOS applications in the form of batch files and specialised utilities interacting with Access objects, tables, forms, queries, reports and macros. A single command button will, after selecting a site (Figure 30), extract data from the database, prepare input files and, for WELL_N, run a series of simulations. An extracted WELL_N input file is displayed in Figure 31.

Figure 30. A drop-down menu is provided to select required site.

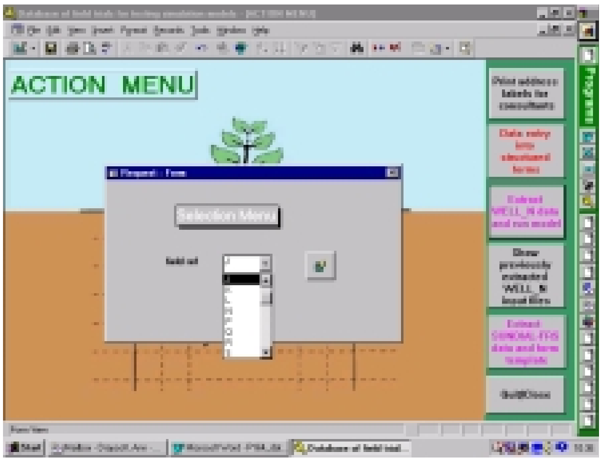
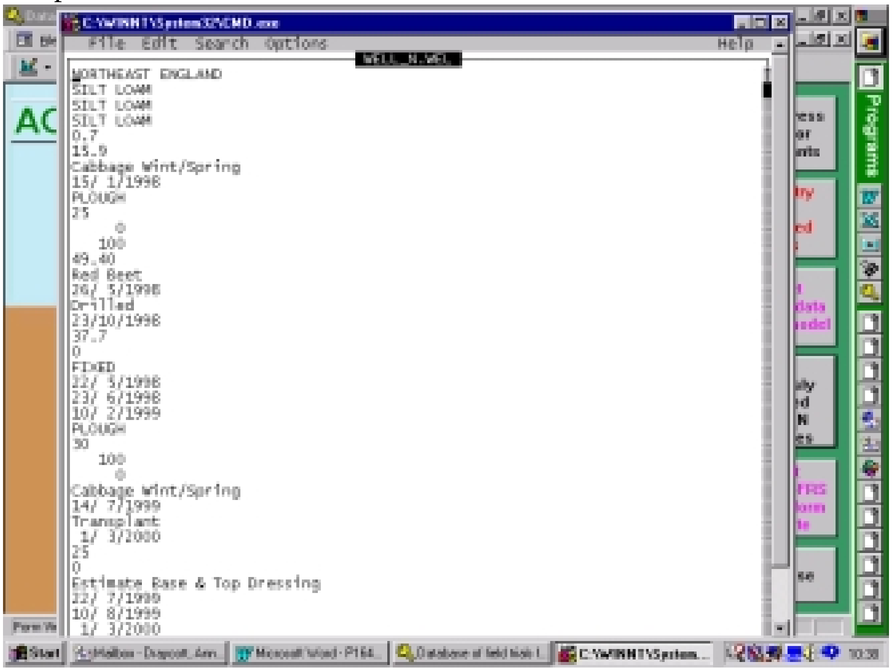
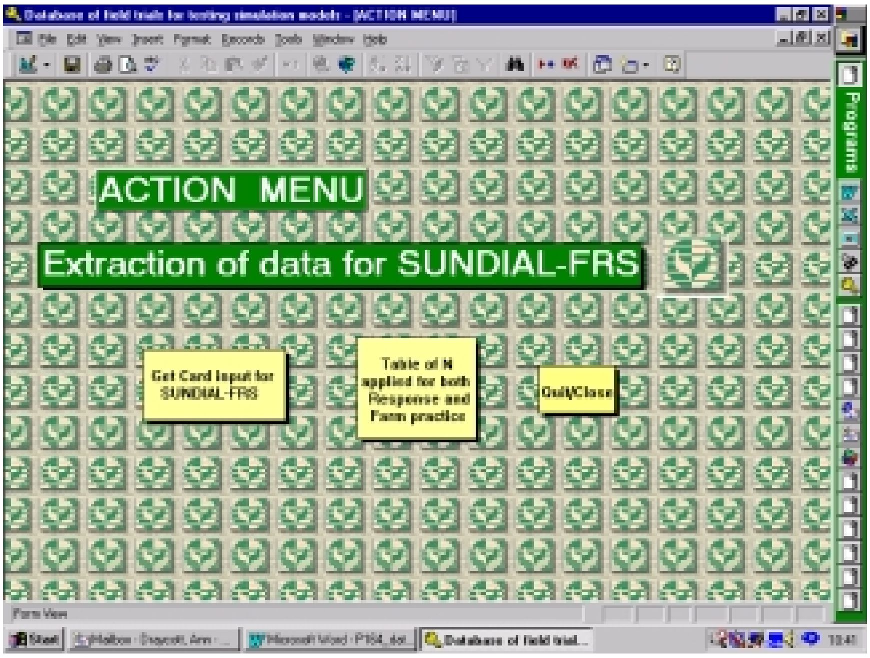


Figure 31. Input files for WELL_N.



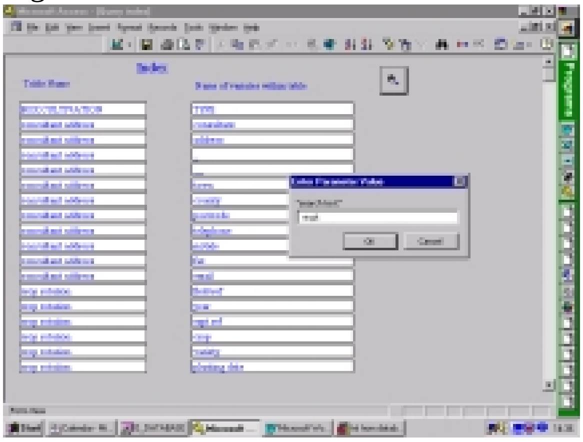
As SUNDIAL-FRS input is more complicated (e.g. names are coded) and was still being modified during final development of the database extractions a decision was taken to produce partially completed templates rather than complete input files (Figure 32). N fertiliser applications for both the response trial and farm practice are presented as reports.

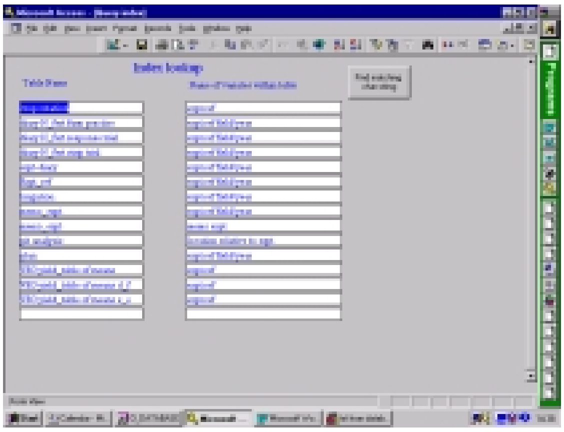
Figure 32. Control Screen directs users in extraction of data to run SUNDIAL-FRS.



To allow data to be found quickly by users forming their own queries a computerised index has been developed to search all the datafields for those whose names contain a user supplied text string, as shown in Figure 33.

Figure 33. Datafield index screen with search button.





3.3. On–Farm Nitrogen Response Trials

Summaries of the results for each individual site are provided in Appendix A.

3.3.1. Weather

Annual rainfall amounts during the trials varied considerably between sites (565 - 930 mm; Table 4). In general, 1998 and 1999 were wetter than the 1992-1996 period. However, for some sites (Sites 11, 12, 18, 22, 30, 35), rainfall remained close to average in both years.

Table 4 Rainfall (mm) recorded at closest meteorological station to the field sites

Sites	1992-1996 average	1998	1999
1	559	706	642
2	611	733	648
3, 34	527	604	565
4	603	746	559
5	665	751	666
6, 10	635	701	639
7, 8, 26, 27, 28, 29	819	897	925
9	658	660	797
11, 12	617	622	617
13	589	744	615
14, 15, 20	591	603	677
16, 23, 24, 31, 32	534	681	715
17, 21	599	686	651
18, 35	768	785	789
19	678	930	914
22	685	701	736
25	647	751	663
30	599	644	643
33, 37	583	684	761
36	755	915	854

However, the patterns of rainfall and temperature are much more important than the total amounts. In 1998, March and April were cool and wet, and the wet soil conditions frequently delayed planting and drilling while heavy rain caused N top dressings to be late or missed altogether. In 1998, cool autumn temperatures slowed growth, and prolonged rainfall in autumn and winter led to slow establishment of autumn-sown arable crops and difficult conditions and soil structural damage during the harvest of some vegetable crops. As a result, some growers abandoned the planned cropping for 1999 in favour of set-aside at three sites (Sites 25, 29 and 32). In 1999, prolonged rainfall during August led to a delayed harvest and consequent poor quality for many cereals.

3.3.2. Field Work

For the arable sites work was focussed into an intensive period of spring soil sampling and fertiliser application (February-March) and a hectic and exhausting harvest period (July-September). Over 15,000 miles were travelled during each growing season, despite combining visits to sites as much as possible.

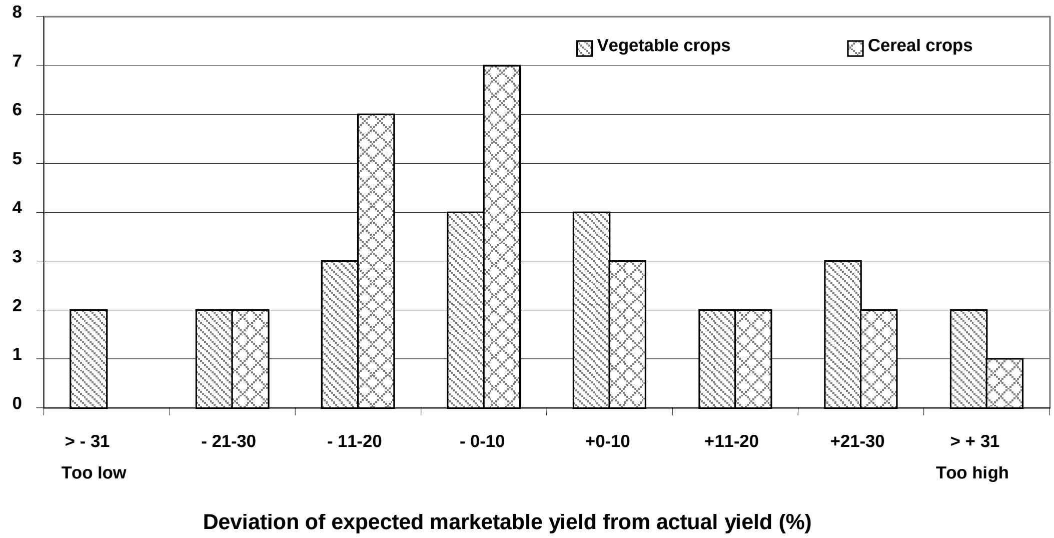
For horticultural crops the disrupted season in 1998 had a knock-on effect on the management of the trial sites, resulting in late changes to selections of both crops and sites. This led to periods of intensive work, particularly with multi-harvested crops, and during the short winter daylight hours. In the first cropping season, 17,000 miles were travelled from Wellesbourne involving 70 separate journeys, and in the second 12,250 miles in 55 trips.

3.3.3. Yields

The effect of inaccurate estimation of marketable yield was highlighted above with reference to site 24/98. Grower forecasts of yield were often inaccurate. Of 22 vegetable and 23 cereal trials, just 36% and 43% respectively gave estimates within ± 10% of the actual yield, as summarised in Figure 34.

With some vegetable crops there can be a discrepancy between the researcher's understanding of marketable yield in the field, as used to guide WELL_N and SUNDIAL-FRS, and the grower's information on saleable produce from the packhouse. However, cereal growers were little better at predicting grain yield and it is clear that there are genuine difficulties in making a realistic assessment of potential yield. Yields are affected by many factors during the growing season, which lie outside the control or prediction of the farmer. It is therefore important to update yield estimates during growth so that fertiliser recommendations can be adjusted.

Figure 34. Accuracy of farmer estimation of marketable yield



The maximum yields recorded in the arable trials were not significantly different to the farm-recorded field yields. These reflected the range of yields obtained on average across the UK *e.g.* 1st wheat 7-12 t ha^{-1}; 2nd wheat 4-11 t ha^{-1}; winter barley 6-9 t ha^{-1}; winter oilseed rape 1.5-6 t ha^{-1}.

Grower forecasts of marketable yield were often inaccurate. Of 22 vegetable and 23 cereal trials, just 36% and 43% respectively gave estimates within ± 10% of the actual yield. This can affect the N requirement of the crop by 25-50 kg N ha^{-1}. Yields are affected by many factors during the growing season, which lie outside the control or prediction of the grower. It is therefore important to update yield estimates during growth so that fertiliser recommendations, which are often guided by the yield estimate, can also be adjusted.

3.3.4. N Response

Over the two seasons, 14 trials showed no marketable yield response to added N fertiliser (Table 5). In some cases this reflected the use of manures (Sites 19 1999, 15 1998, 15 1999) or the use of basal fertiliser containing N (Site 19 1999) before the trial was established. High variability of bulb onions at site 22 in 1998 was caused by patchy recovery from severe hail damage early in the season. *Septoria* increased yield variability in wheat at high N rates at Site 3 in 1999. Lodging affected the winter barley at Site 2 in 1998. Both reduced the impact of increasing rates of N application on yield. The lack of response to N by potato at Site 6a 1998 is not unexpected with this potato variety. With other crops, there was no obvious reason for a lack of increase in yield with increasing N, for example the two carrot crops, at either the early or commercial harvest (Sites 25 and 27), or dwarf beans (Site 33). Only two of the seven winter oilseed rape crops in the trials (Sites 1 1998, 13 1999) showed a significant increase in yield in response to the addition of N fertiliser. However, in most of the winter oilseed rape trials, total dry matter yield and N uptake increased significantly with increasing N application. While the size of the crop canopy increases with increasing N application, this does not necessarily cause an increase in rape seed yield, due to shading of pods and increased disease susceptibility. In some cases yield may also have been restricted by sulphur availability, since farm applications of sulphur were made within the N fertiliser applications.

The optimum N fertiliser application could be determined from a linear plus exponential relationship for 37 trials. For 10 trials the optimum fertiliser application was not contained within the range of N applications tested, leading to an unbounded linear plus exponential curve or a straight line relationship between N applied and marketable yield (Table 5). Where responses were fitted to both the total dry matter and marketable yields for vegetable crops, the optimum N requirements were not significantly different.

In cereals the application of increasing amounts of N fertiliser generally increased the concentration of N in both grain and straw. With no additional N fertiliser the N content of wheat grain ranged from 1.2 – 2.3 %, with 1.5 % N as the most common value (6 sites). The critical N content of grain indicating N sufficiency is usually taken as 2%. At 3 sites (Site 15 1998, 17 1998 and 14 1999) the N content of the wheat grain was ≥ 2% in the absence of any additional N fertiliser; in these years sites 14 and 15 had received autumn manure applications. At the remainder of the sites, between 50 and 200 kg N ha^{-1} were required to increase the N content of the wheat grain to ≥ 2%, with 22 kg N ha^{-1} required on average to increase the %N in the grain by 0.1%. Following celery (Site 18 1998), set-aside (Site 16 1998) and sugar beet (Site 20 1999) even the maximum application of additional N fertiliser within the trial did not increase the grain N content above 2%. However, these circumstances were not replicated within the trials and it is unclear whether this is a true effect of the previous crop or due to a peculiarity of the site, timing of N application or season. The N content of cereal straw was typically 0.3 - 0.4 % in the absence of additional N fertiliser. However, at N applications above the optimum, the N content of straw increased to 0.7 – 1 % N.

In oilseed rape, the N content of the grain and straw generally increased with the addition of N fertiliser and the percentage of oils was generally reduced with increasing application of N fertiliser. The N content of sugar beet root also increased significantly with increasing N fertiliser application. However, with the exception of the peat soil, application of N did not significantly increase the N content of potato tubers.

N uptake where no fertiliser was applied varied from 21 to 267 kg N ha^{-1}; this reflects inherent differences in the fertility of the soil and the period and duration of crop growth. Salad onion and early spinach crops had the lowest N uptakes, where no fertiliser was applied. The largest N uptake in the absence of fertiliser was by a winter wheat crop after vining peas, which had also received 45 t ha^{-1} of pig manure in the previous autumn (Site 15, 1998). Even within the 20 winter wheat crops studied, N uptake in the absence of fertiliser ranged from 48.4 to 266.6 kg N ha^{-1} and showed no clear relationship with the N index determined from the previous cropping (MAFF, 1994). However, where two consecutive wheat crops were grown in the trials (Sites 5, 11, 17), the unfertilised N uptake of the first winter wheat was greater than that of the second winter wheat.

Table 5. Number of trials in various categories of model fit

Best-fit model	Optimum	Number of trials	Site & Year
No model could be fitted	-	3	14 98, 18 98, 31 99.
No response to applied N	0	14	2 98, 2 99, 4 99, 8 98, 9 99, 12 99, 15 98, 15 99, 19 99, 22 98, 25 98, 27 98, 33 98, 34 99.
Linear response to applied N	None	7	1 98, 1 99, 4 98, 6 98, 7 98, 26 98, 30 98
Linear plus exponential fit			
	> maximum level tested	3	7 99, 19 98, 31 98.
	Optimum within range, 95% confidence interval could not be estimated	14	5 98, 5 99, 8 99, 10 98, 11 98, 12 98, 13 99, 17 98, 22 99, 24 98, 34 98, 35 98, 36 99, 37 98.
	Optimum within range, 95% confidence interval estimated	23	3 98, 3 99, 6 99, 9 98, 10 99, 11 99, 13 98, 14 99, 16 98, 16 99, 17 99, 20 99, 21 99i, 21 99ii, 23 98, 26 99, 28 98, 28 99, 29 98, 30 99, 32 98, 36 98, 37 99.

3.3.5. Soil Mineral N

Spring mineral N to 90 cm varied from 19 to 180 kg N ha^{-1}, where no manure or fertiliser had been applied (Tables 6 and 7).

Table 6. Soil mineral N (NO_3 plus NH_4) measured in soil samples taken in early spring (winter crops) or pre-planting (spring and summer crops) in 1998.

Site	Crop	Previous crop	Date of sample	Soil mineral N (kg ha^{-1}) 0-30 cm	30-60 cm	60-90 cm
1	W. OSR	W. barley	11/02/98	44	22	15
2	W. barley	W. wheat	12/02/98	42	26	41
3a	W. wheat	W. OSR	13/02/98	23	12	8
4	W. wheat	W. wheat	13/02/98	37	30	40
5	W. wheat	Field pea	18/02/98	43	37	35
6a	Potato	W. wheat	18/02/98	34	19	*
7	W. OSR	W. wheat	16/02/98	39	25	20
8	W. wheat	Field pea	16/02/98	56	33	40
9	W. wheat	S. OSR	17/02/98	42	28	34
10	W. wheat	Field pea	19/02/98	30	*	*
11	W. wheat	W. OSR	23/02/98	37	31	17
12	W. wheat	W. wheat	23/02/98	35	34	*
13	W. barley	W. wheat	24/02/98	30	34	30
14	W. OSR	W. wheat	25/02/98	25	22	27
15	W. wheat	Vining pea	25/02/98	54	53	109
16	W. wheat	Set-aside	27/02/98	23	26	53
17	W. wheat	W. bean	27/02/98	59	51	54
18	W. wheat	Celery	02/03/98	16	8	11
19	W. wheat	W. OSR	03/03/98	33	27	40
20	Sugar beet	W. wheat	14/04/98	40	31	18
22	Bulb onion	W. wheat	10/02/98	32	33	78
23	Bulb onion	W. wheat	16/02/98	29	20	19
24	Calabrese	Cabbage	06/03/98	39	46	95
25	Carrot	Potato	17/03/98	23	32	25
26	Leek	Lettuce	21/04/98	35	27	28
27	Carrot	W. wheat	21/04/98	23	25	18
28	Cauliflower	Cauliflower	29/04/98	27	20	20
29	Brussels sprout	W. wheat	28/04/98	19	20	20
30	Red beet	Cabbage	29/04/98	58	50	50
31	Brussels sprout	W. wheat	01/05/98	43	24	18
32	Cabbage	Brussels sprout	28/05/98	43	33	28
33	Dwarf bean	Salad onion	30/06/98	31	27	22
34	Cauliflower	Calabrese	22/07/98	8	6	5
35	Lettuce	Lettuce	18/08/98	103	41	35
36	Lettuce	Carrot	06/07/98	19	33	29
37	Salad onion	W. wheat	06/01/99	34	34	37

* No sample taken due to shallow soil

Table 7. Soil mineral N (NO_3 plus NH_4) measured in soil samples taken in early spring (winter crops) or pre-planting (spring and summer crops) in 1999.

Site	Crop	Previous crop	Date of sample	Soil mineral N (kg ha^{-1})		
				0-30 cm	30-60 cm	60-90 cm
1	W. wheat	W. OSR	05/03/99	39	39	35
2	W. OSR	W. barley	11/02/99	36	18	25
3b	W. wheat	Field pea	16/02/99	42	22	21
4	W. OSR	W. wheat	16/02/99	47	28	18
5	W. wheat	W. wheat	04/03/99	34	39	32
6b	W. wheat	Field pea	19/02/99	29	21	*
7	W. wheat	W. OSR	18/02/99	64	43	34
8	W. barley	W. wheat	18/02/99	37	38	36
9	S. OSR	W. wheat	10/04/99	285	105	45
10	Potato	W. wheat	31/03/99	52	*	*
11	W. wheat	W. wheat	04/03/99	74	43	25
12	W. OSR	W. wheat	15/02/99	45	35	*
13	W. OSR	W. wheat	15/02/99	30	30	18
14	W. wheat	W. OSR	02/03/99	30	41	59
15	Sugar beet	W. wheat	09/04/99	137	82	94
16	Cabbage	W. wheat	07/04/99	35	15	17
17	W. wheat	W. wheat	26/02/99	42	58	41
19	Potato	W. wheat	19/04/99	Sampled after top-dressing		
20	W. wheat	Sugar beet	02/03/99	23	27	25
21	Spinach	W. barley	13/04/99	56	54	50
21	Spinach	Spinach	04/08/99	96	71	35
22	Parsnip	Bulb onion	12/05/99	53	39	21
25	Set-aside	Carrot	25/05/99	11	7	15
26	Lettuce	Leek	08/04/99	27	15	10
28	Cauliflower	Cauliflower	11/05/99	40	43	42
29	Set-aside	Brussels sprout	11/05/99	65	42	21
30	Cabbage	Red beet	26/05/99	23	29	17
31	Cauliflower	Brussels sprout	26/05/99	57	27	18
32	Set-aside	Cabbage	19/05/99	56	23	28
34	Cauliflower	Cauliflower	22/06/99	84	23	16
36	Potato	Lettuce	08/04/99	19	55	41
37	Salad onion	Salad onion	07/07/99	105	50	31

* No sample taken due to shallow soil

Where manures (Site 15 1998, 15 1999, 9 1999) or fertiliser (Site 19, 1999) had been applied before soil sampling, mineral N levels were increased significantly. Any relationship between spring mineral N and previous cropping was obscured by the varied soil types and climates *e.g.* both the extremes quoted above followed calabrese (Sites 34, 1998 and 24 1998).

Surprisingly there was no significant relationship between spring mineral N and crop N uptake on zero plots, even when only the combinable crops or winter wheat alone were included. This relationship may have been improved if crop N uptake in spring had also been measured, which normally ranges between 15 and 50 kg N ha^{-1}, so that soil N supply rather than solely mineral N could have been considered.

Residual soil mineral N measured at harvest in the fertilised plots increased significantly above the level measured in the plots which had received no fertiliser in 24 of the 65 trials. An increase in residual mineral N was more common following oilseed rape than the other combinable crops and also occurred where lodging restricted the yield of winter barley (Site 2 1998). In addition, an increase in residual mineral N was seen at high rates of N application in potatoes. Both potatoes and oilseed rape return significant amounts of N to the soil in leaf litter during the growing season and this may contribute to the increase in soil mineral N at harvest in these crops. Many of the increases in soil mineral N where high rates of application were used on the vegetable crops were likely to be due to unused fertiliser.

3.4. Evaluation of Decision Support System

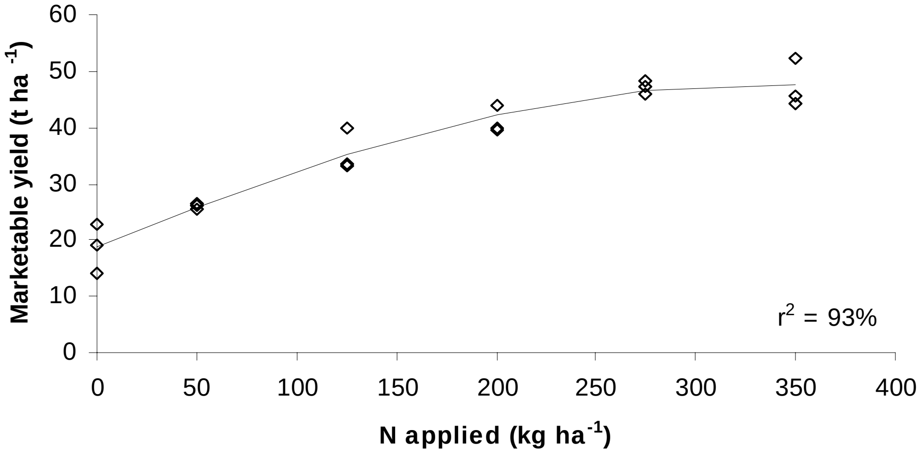
The objectives of the evaluation of the decision support system were to determine the likely accuracy of the fertiliser recommendations, to assess the simulations of N turnover on working farms, and to identify which model should be used to simulate a particular crop. The decision support system was evaluated in 2 ways:

1. Comparison of the predicted optimum N application with the optimum N rate calculated from the N response trials; and
2. Comparison of the simulated N turnover with the soil mineral N and crop N offtake measured in the trial plots.

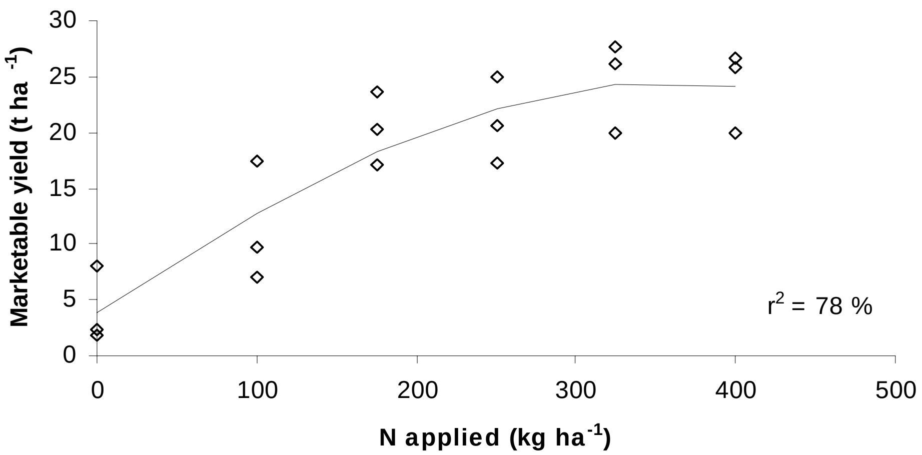
However, both types of evaluation were subject to difficulties in analysis associated with the complexity and variability of the experimental results, similar to those discussed by Sutherland (1986) and Goodlass (1997). The results from these trials show higher spatial variability than would be anticipated in a similar trial run on an experimental station, making it difficult to obtain reliable estimates of the optimum fertiliser dressing. This may be attributable to the differences in previous crop management and site history that inevitably occur on working farms. The spatial variability measured in yield is illustrated in figure 35. Where soils were known to be very uniform, e.g. Site 16, variation in yield between replicates was often very low (Figure 35a). However, at many other sites even where linear plus exponential yield response curves could be fitted (with highly significant correlation) the variation in yield between replicates was high, with a coefficient of variation of 10-20%. At some sites the coefficient of variation reached 29% between replicates in wheat (Figure 35b) and 47% between replicates in cabbage (Figure 35c).

Figure 35. Variation in Yield on Replicated Plots

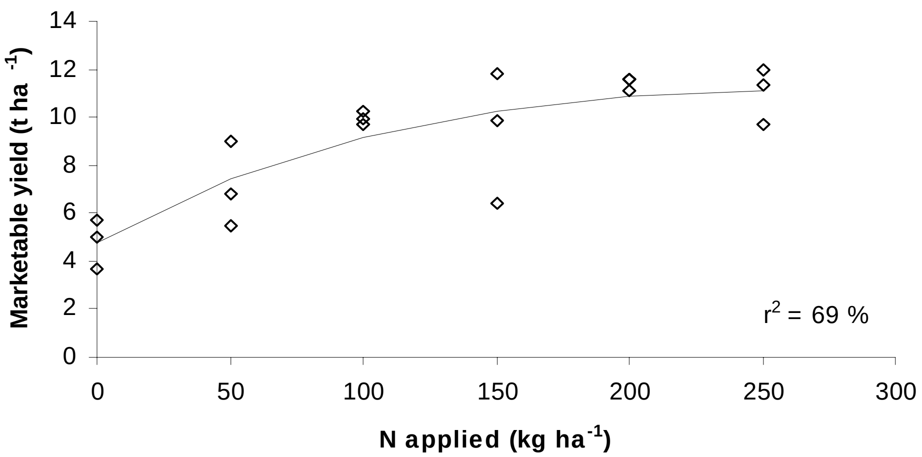
a) Site 16 1999, cabbage



b) Site 11 1999, winter wheat



c) Site 30 1999, Savoy cabbage



The advantage of process based simulation models, such as SUNDIAL and WELL_N, over statistical models, such as RB209 (MAFF, 1994) is the greater potential for simulating season and site specific variation in N turnover. However, despite high variation between replicate plots within a field, the data entered for the replicates were identical in SUNDIAL, and differed by only the spring soil mineral N values used in WELL_N. Soil measurements taken at the start of the trial indicated the inherent spatial variability of the sites. Plot specific measurements such as initial soil organic N and spring soil mineral N should help to capture the variability, and improve the accuracy of predicted optimum N rates and N turnover.

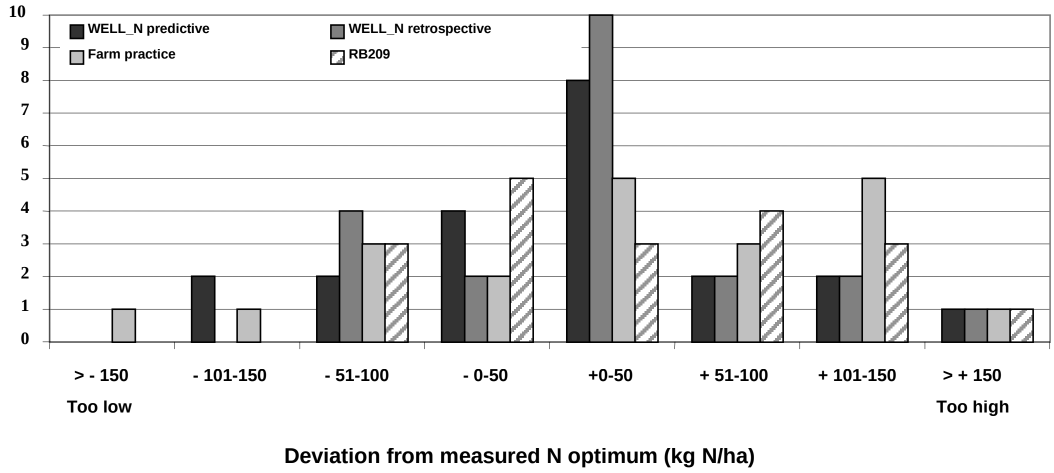
In the next 2 sections (3.4.1 and 3.4.2), the evaluations of WELL_N and SUNDIAL-FRS are described separately because different crops and soils are simulated by the 2 models. In the final section (3.4.3), the performance of the integrated system, Nitrogen-FRS, is evaluated against farm practice.

3.4.1. WELL_N Evaluation

Recommended Rates of N: Vegetables

Predictive and retrospective recommendations from WELL_N, RB 209 (6th edn.) and farm practice are compared in Figure 36 with the calculated N optima for the vegetable trials (including sugar beet and potatoes). Trials where it was not possible to calculate optima are excluded. A bandwidth of 50 kg N ha^{-1} was considered appropriate given the large errors associated with the calculation of the optima (Section 2.3.5), the variable recommendation interval between different recommendation systems and the errors in farm application rate.

Figure 36. Vegetable crops: Comparison of WELL_N and RB209 recommendations and farm practice with measured N optima.



Predictive and/or retrospective WELL_N recommendations were within ± 50 kg N ha^{-1} of the measured optima in 57% of the trials compared to 42% for RB209 and 33% for farm practice. Overall, WELL_N was superior to both RB209 and farm practice, but two trials (24/98, 22/99) underestimated and three (32/98, 33/98, 37/98) overestimated N requirement by more than 101 kg N ha^{-1}. Detailed results for all trials are given in Appendix B, but these five trials are also examined here.

In 24/98 the predictive underestimation of requirement was due to the marketable yield of calabrese being 30% higher than expected (retrospectively, with achieved yields, the recommendation was within 50 kg N ha^{-1}). Underestimation in 22/99, parsnip, was possibly due to weed competition which would have increased overall N requirement in the field, but also to the uncertainties in estimating the date of maximum potential yield for this overwintered crop, where foliage had died back before the commercial harvest. Apart from winter cereals, WELL_N is not fully parameterised for overwintered crops. Further work is required to determine parameters for the overwinter growth phase of vegetable crops.

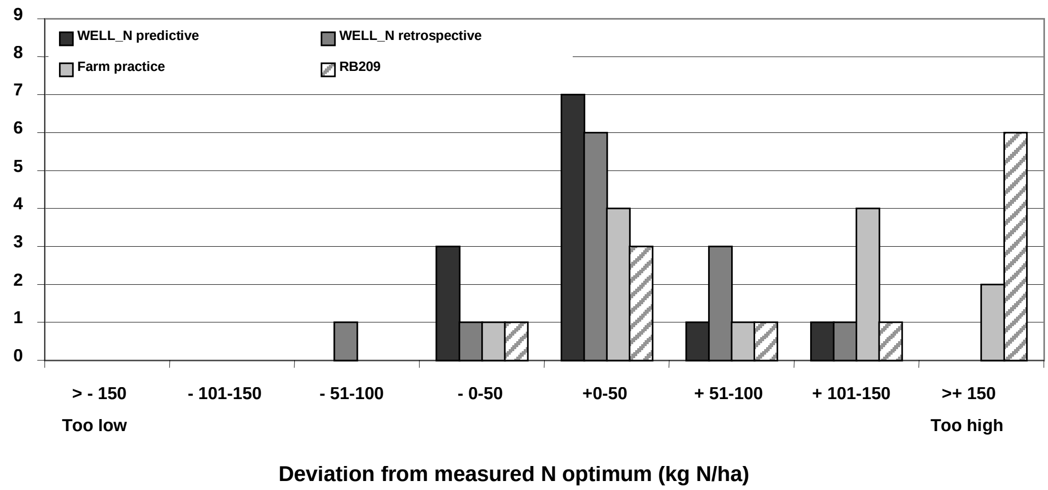
In the three trials where WELL_N overestimated N requirement, this occurred both predictively and retrospectively. In the Dutch white cabbage trial, 32/98, on a silt soil, both the SUNDIAL-FRS recommendation and farm practice were also above the calculated optimum. It is noticeable (see Appendix B) that both models underestimated crop N uptake and soil mineral N content when compared to the field data, suggesting that mineralisation rate was higher than expected. Indeed, estimating mineralisation from changes in spring and post harvest soil mineral N and plant N uptake on the zero N plots at this site indicated a rate more than double the default used in WELL_N. The rate was also higher than that estimated for other local marine silts used in the project, suggestive of unrecorded past applications of organic manures. At site 33/98, dwarf bean, it is likely that in the warm summer conditions prevailing, the model underestimated the speed of residue breakdown following the ploughing in of an unharvested salad onion crop five days prior to drilling the beans. For the overwintered salad onion crop (37/98), RB209, farm practice and WELL_N application rates agreed closely and out-yielded the low calculated optimum by 16%. There were no obvious reasons for the WELL_N overestimation as estimates of crop N uptake and soil mineral N were good and, although the crop was overwintered, the model run was updated with a spring measurement of plant size. WELL_N is not specifically parameterised for salad onions and was run as bulb onions, albeit with a lower expected yield. Dynamic models will only be of value in giving a broad indication of N requirement for salad onions, since farm practice is dominated by the use of N to control timing of crop maturity and leaf colour.

At the peat site (36), using mineralisation rates calculated from site data for lettuce and potato (Section 2.4), WELL_N gave predictive recommendations within 50 kg N ha^{-1}, and yields within 5% of the optimum. However, the calculated rates varied markedly between the two crops, 2.11 and 0.72 kg N ha^{-1} day^{-1} at 15.9ºC for lettuce and potato respectively. Further work is needed to enable the model to be reliably used on peat soils.

Recommended Rates of N: Cereals

Recommendations for the cereal trials are summarised in Figure 37. The predictive recommendations for WELL_N were within ± 50 kg N ha^{-1} of the measured optima in 83% of the trials. This compared with 50% of the trials for the retrospective recommendation, 42% for farm practice and 33% for RB209.

Figure 37. Cereal crops: Comparison of WELL_N and RB209 recommendations and farm practice with measured N optima.



In contrast to the vegetable trials, there was a tendency for each recommendation method to overestimate N requirement. This was particularly marked for RB209 and farm practice where rates deviated by more than 101 kg N ha^{-1} from the measured optima in 58 and 50% of the trials, respectively. WELL_N overestimated by the same amount in just one trial, 2/98, representing just 8% of its recommendations. At this site, lodging at high rates of N had reduced grain yields and lowered the optimum.

This summary is based on the 10 winter wheat and 2 winter barley trials which had detectable optima and excluded trials where organic manures had been applied. Also excluded are the 6 cereal trials on the structured clay soils of the Hanslope and Denchworth series. WELL_N was not specifically developed for highly structured soils and does not differentiate the leaching function and default mineralisation rate from those used with unstructured soils.

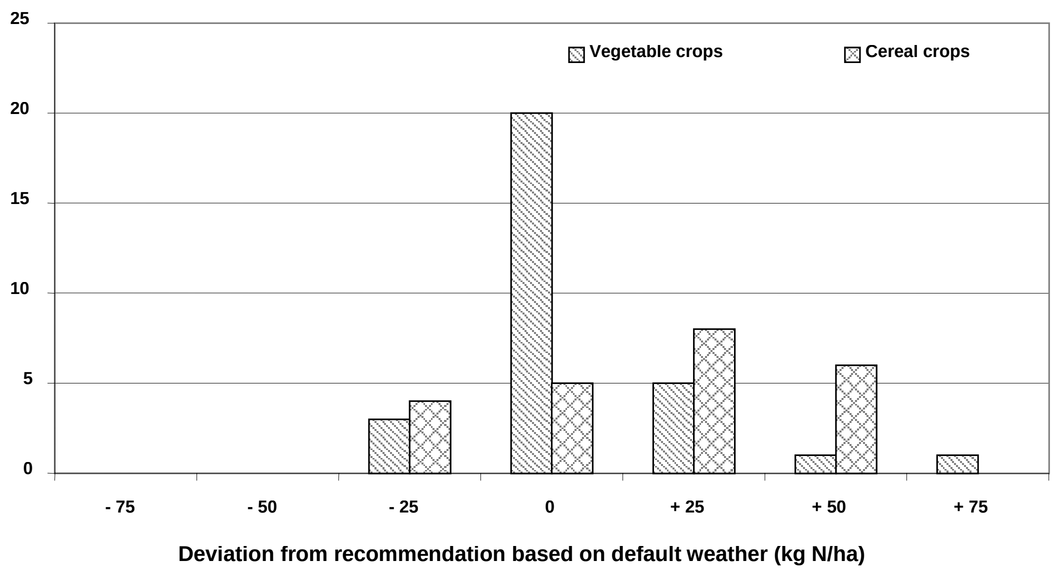
Thus no account is taken of preferential water flow between aggregates and in cracks in the soil profile, nor of adsorption/fixing of N by clay minerals. Nevertheless, WELL_N, with 2 of the 6 trials within 50 kg N ha^{-1} of the calculated optima, performed no worse than SUNDIAL-FRS. RB209 and farm practice did slightly better, with 3 out of the 6 trials meeting the criteria used.

Effect of Weather on Recommendations

It was noted in Section 3.3.1 that, during the two years of the field trials, most sites experienced higher than average rainfall, particularly in the spring. To investigate the impact of this on WELL_N, a comparison was made between recommendations obtained by using either default or actual weather throughout the growing season. The results are presented in Figure 38, which shows the change in recommended rate of N when actual weather was used.

As expected, given the two wet seasons, there was a tendency for recommendations to be higher when actual weather was compared to default weather. This was least marked with the vegetable crops, where 67% of the trials showed no change. Three sites, 26/98 (Lancashire) 28/98 (Lancashire), and 35/98 (Sussex) showed a decrease of 25 kg N ha^{-1} and one 22/98 (Suffolk) a 75 kg N ha^{-1} increase when actual weather was used. In contrast to the vegetable sites, only 21% of cereal trial recommendations were unaffected by the weather data used, but 63% showed increases of 25-50 kg N ha^{-1}. There are two possible explanations for this. First, the N applications to the winter cereal trials were made earlier in the year than on most of the vegetable trials and were consequently more at risk from leaching in the early spring. Second, the trial applications of N to the cereals in the first year were applied as a single dressing, again increasing the risk of leaching. For the purposes of comparison with trial results, the model was run with the N application dates used in the trial. In practice it would be advisable to run the model with updated actual weather immediately prior to each top-dressing.

Figure 38. Effect of using actual weather on WELL_N recommendations

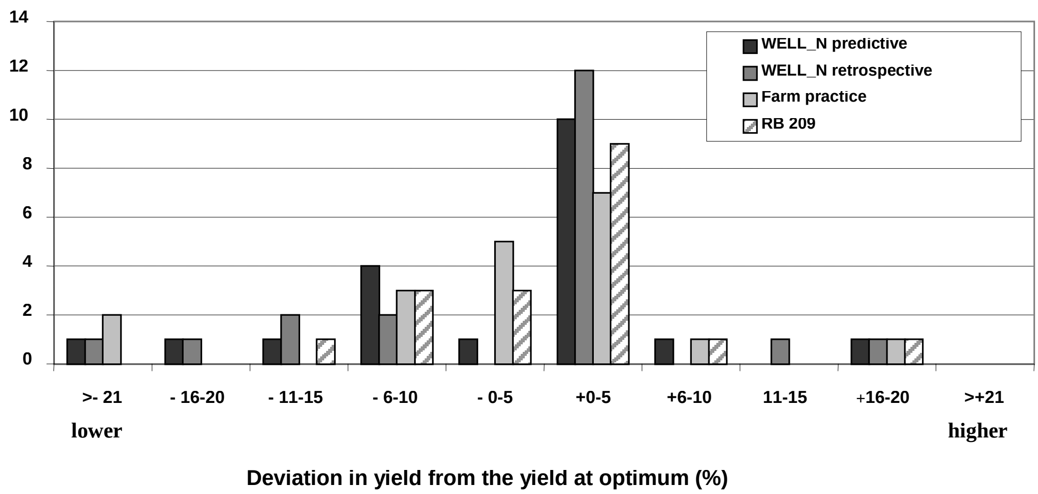


Although reference is made to ‘actual’ weather it should be realised that this was obtained from meteorological stations sited between 2 and 62 km from the trial and therefore may not closely reflect the weather experienced at the site. In particular, heavy localised showers, which can be important in determining leaching shortly after fertiliser applications, may have been missed. It is advisable whenever possible to use meteorological data, particularly rainfall, recorded on site.

Effect of recommendations on marketable yield
To estimate the potential effect of the recommended rates on marketable yield, yield at the recommended rate was expressed as a percentage of the yield at the optimum. For vegetable crops this is shown in Figure 39.

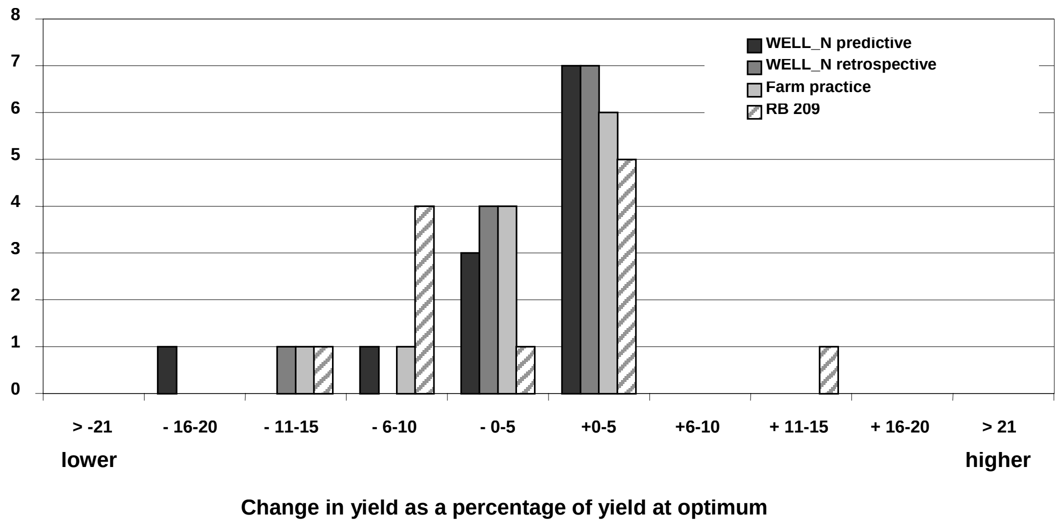
Using RB 209 or WELL_N predictively and retrospectively provided recommended rates which gave the same or higher marketable yields than those calculated for the optima in 60-70% of the trials. With farm practice this was achieved in just 47%. In trials 24/98 and 22/99, where WELL_N grossly underestimated N requirement for the reasons explained, the recommendations also led to large reductions in yield. Yield losses greater than 15% also occurred at sites 21/99(1), spinach (predictive and retrospective) and 37/99, salad onion (retrospective). Spinach is a fast growing crop, making it difficult to estimate the optimum from a single harvest. The crop grown with the WELL_N recommendation of 125 kg N ha^{-1} was judged by the farmer on the day of harvest to be of marketable quality, while with the 200 kg N ha^{-1} rate (close to the calculated optimum of 201 kg N ha^{-1}) was judged overmature. The salad onion crop, as noted in Appendix B, was very low yielding due to an uneven stand resulting from a cloddy seedbed. Using the low achieved dry weight in the retrospective analysis gave a low recommendation and a 24% lower marketable yield than at optimum. Yield per unit area under these conditions is an average of good and bad areas. To grow the good areas needs a higher N requirement than that given by a recommendation based on a low average yield. It is clearly wrong to compensate for patchy growth by reducing estimated potential yield.

Figure 39. Vegetable crops: Effect of WELL_N and RB 209 recommendations and farm practice on marketable yield.



The affect of recommendations on yield of cereals (excluding heavy clays) is given in Figure 40. Given a generally flat response to N at many sites, the yields obtained with the recommended rates and farm practice did not generally deviate by much from that calculated for the optima. WELL_N recommendations and farm practice gave yields within ±5% of the optimum in 83-92% of the trials, with RB 209 achieving considerably less at 50%. At only one site, 20/99, did a WELL_N recommendation reduce yield by more than 11%. Here, a winter wheat crop followed sugar beet for which details of residue incorporation were unavailable. Default values of residue appear to have overestimated N supply leading to an underestimate of N requirement and loss of yield.

Figure 40. Cereal crops: Effect of WELL_N and RB 209 recommendations and farm practice on marketable yield.



Crop N Uptake and Soil Mineral N

In comparison with measured values, WELL_N showed a tendency, with both vegetables and cereals, to overestimate crop N uptake and to underestimate mineral N remaining in the soil at harvest. Data for individual trials are shown in the appendices. Simulated values of crop N plus soil mineral N are shown plotted against measured values for all trials: vegetables in Figure 41 and cereals in Figure 42 (excluding clay soils). These XY plots show data points scattered about the lines of perfect agreement.

Figure 41. Vegetables: Simulated crop N + soil mineral N plotted against measured values. The line shown is the line of perfect agreement.

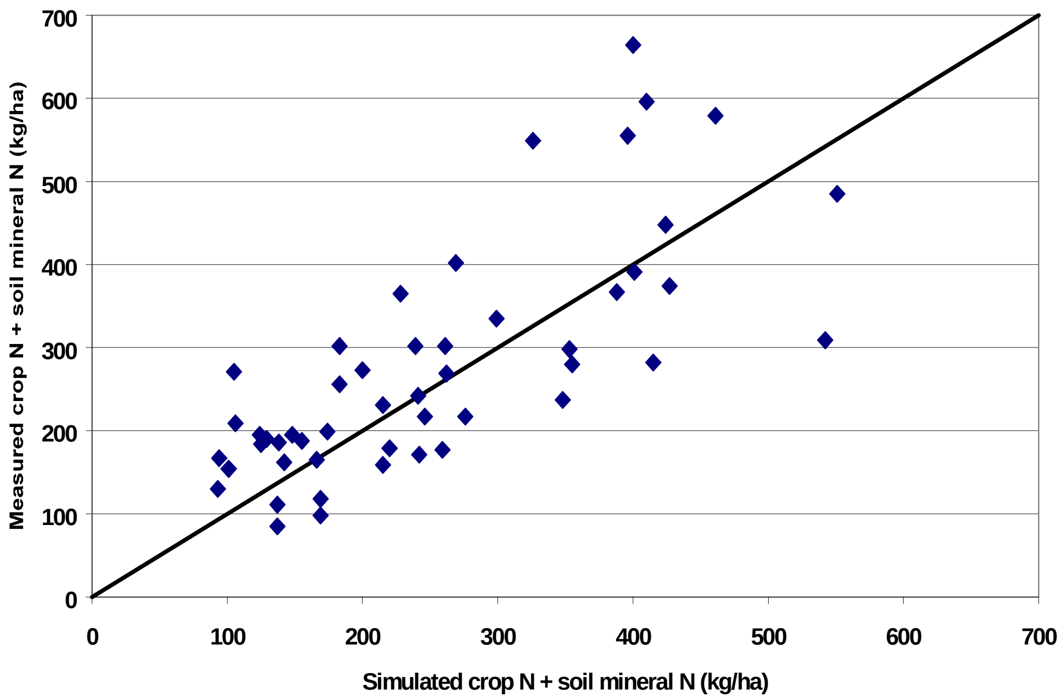
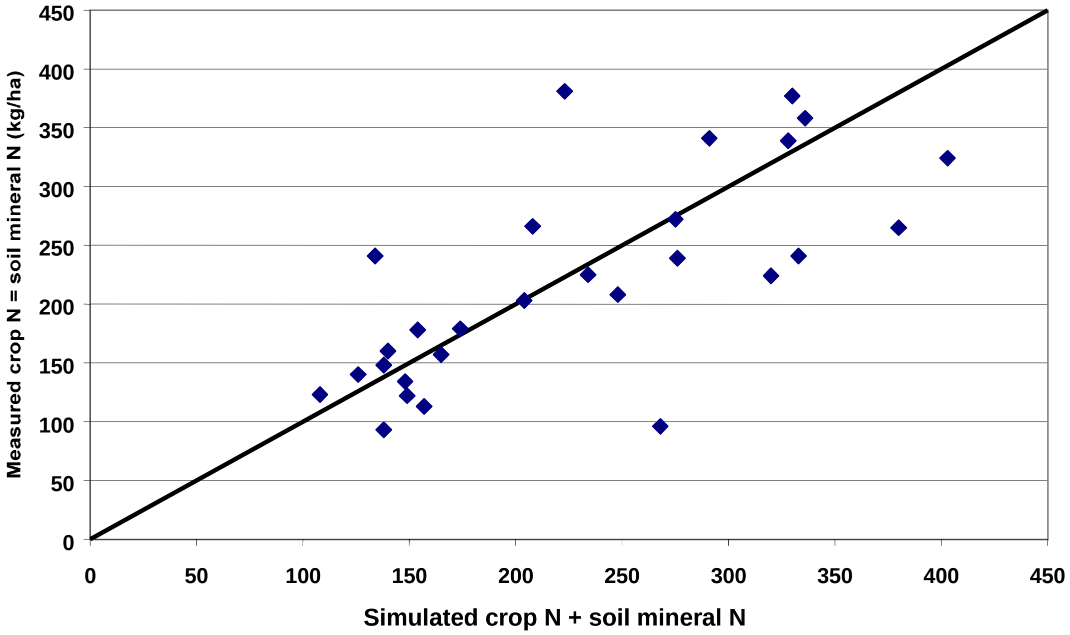


Figure 42. Cereals: Simulated crop N + soil mineral N plotted against measured values. The line shown is the line of perfect agreement.



Conclusion

The overall conclusion from both the vegetable and cereal sites is that, in the majority of circumstances, the use of WELL_N gives much the same yield as following RB209 or farm practice. WELL_N, however, is more likely to recommend the correct rate of N, thereby reducing fertiliser costs and wastage to the potential benefit of the environment.

3.4.2. SUNDIAL-FRS Evaluation

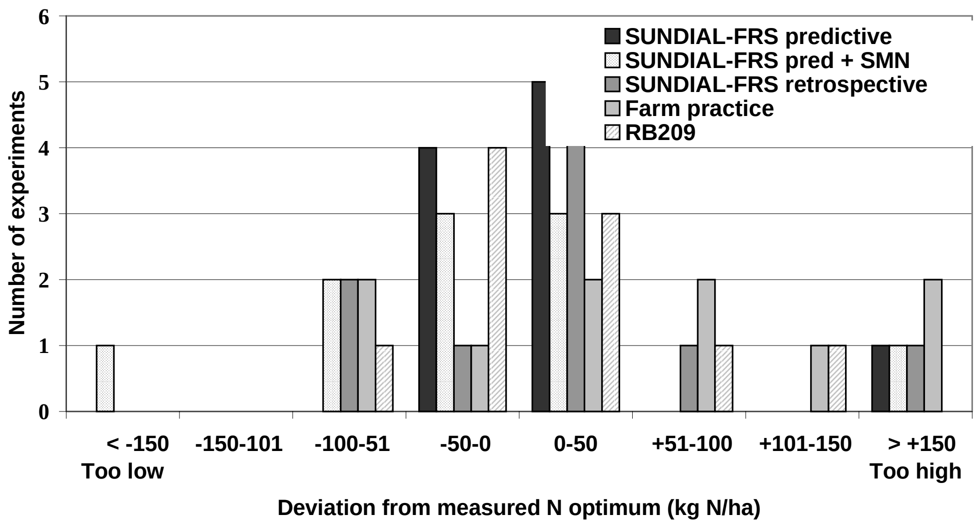
Recommended Rates of N: Vegetables

Predictive and retrospective recommendations from SUNDIAL-FRS, RB 209 (6th edn.) and farm practice are compared in Table 8 and Figure 43 with the calculated N optima for the vegetable trials (including sugar beet and potatoes). The SUNDIAL-FRS predictive recommendations use the expected marketable yield and default weather data from fertiliser application to harvest. The predictive + SMN recommendation uses spring SMN measurements (0-90cm) as an input, but relies on default weather and the predicted yield. A farmer might use this method to improve site specificity. The retrospective recommendations are based on actual yields and weather, and include spring SMN measurements. Comparisons were only possible at 10 sites, as trials where it was not possible to calculate optima are excluded, as are trials where there was no response to N (i.e. the optimum was zero). Similarly, trials with crops that are not parameterised in SUNDIAL-FRS were excluded. All sites where cauliflower was grown were also excluded, as the crop parameters were revised using the data from the trials. As in the WELL_N evaluation, a bandwidth of 50 kg N ha^{-1} was considered appropriate given the large errors associated with the calculation of the optima (Section 2.3.5), the variable recommendation interval between different recommendation systems and the errors in farm application rate.

Table 8. Vegetable crops. Summary of deviation of farm practice, SUNDIAL-FRS and RB209 recommendations from measured N optima. Expressed as percentage of trials.

Difference from optima	SUNDIAL Predictive	SUNDIAL Predictive + SMN	SUNDIAL Retrospec-tive	Farm practice	RB209
% within 50 kg N	90	60	60	30	70
% within 100 kg N	90	80	90	70	90
% over 100 kg N	10	20	10	30	10
Number of trials	10	10	10	10	10

Figure 43. Vegetable crops: Comparison of SUNDIAL-FRS and RB209 recommendations and farm practice with measured N optima.



90% of predictive SUNDIAL-FRS recommendations were within ± 50 kg N ha^{-1} of the measured optima compared to 70% for RB209 and 30% for farm practice (Table 8). At only one of the trials was the SUNDIAL-FRS predictive recommendations outside this range, at 32/98 (Dutch white cabbage).

Detailed results for all trials are given in Appendix B, but these two trials are also examined here. At site 32/98 the SUNDIAL recommendation was 220 kg N ha^{-1} above the optimum. WELL_N also over-estimated the optimum at this site. See discussion in the WELL_N section for further details.

Including spring SMN measurements tended to reduce the recommendations, so that fewer of the predictive recommendations were within ± 50 kg N ha^{-1} of the measured optima (60%). The methodology for using simple measurements such as SMN to improve site specificity requires further development. The SMN measurement has been used to adjust the modelled value, so resetting the model to correct the size of any loss or transformation processes.

However, if the model accurately simulates the *size* of processes but there is a slight discrepancy in *timing*, a simple adjustment of modelled SMN will introduce additional error as observed in these trials. A SMN measurement is easy to take and has potential to greatly improve recommendations. However, a simple adjustment of SMN is inadequate: development of a more complex methodology is needed.

Including actual weather and yield had no overall effect on the number of recommendations within 50 kg N ha^{-1} of the optima, but reduced the number of recommendations which were more than 100kgN/ha outside this range to one (10/99). At this site, the predictive recommendation for the potatoes was reasonable, being within 20 kg N/ha of the optimum. However, it was based on an expected yield which was much lower than that actually achieved (60 t/ha compared to a maximum yield of 82 t/ha). This suggests that SUNDIAL-FRS may need further work refining potato parameters under conditions of high yields.

Recommended Rates of N: Arable

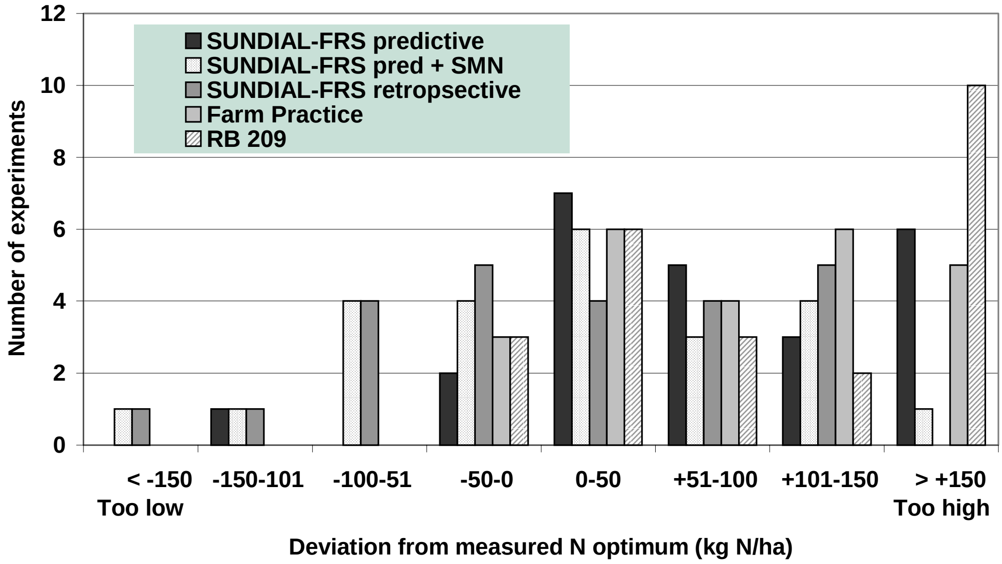
Predictive, predictive plus spring SMN and retrospective recommendations from SUNDIAL-FRS, RB 209 (6th edn.) and farm practice are compared in Table 9 and Figure 44 with the calculated N optima for the 24 arable trials which had detectable optima. Trials where it was not possible to calculate optima are excluded. Trials where there was no response to N (i.e. the optimum was zero) are included. There were 17 winter wheat, 3 winter barley and 4 oilseed trials. Unlike the WELL_N comparison, oilseed rape and trials where organic manures had been applied were included.

The predictive recommendations for SUNDIAL-FRS were within ± 50 kg N ha^{-1} of the measured optima in 38% of the trials (Table 9). This compared with 38% of the trials for farm practice and RB209. Including spring SMN measurements increased this to 42%, with fewer recommendations more than 100 kg N ha^{-1} out. There was no further benefit from using real weather and yields.

Table 9. Arable crops. Summary of deviation of SUNDIAL-FRS and RB209 recommendations and farm practice from measured N optima. Expressed as percentage of trials.

Difference from optima	SUNDIAL Predictive	SUNDIAL Predictive + SMN	SUNDIAL Retrospec-tive	Farm practice	RB209
% within 50 kg N	38	42	38	38	38
% within 100 kg N	58	71	71	54	50
% over 100 kg N	42	29	29	46	50
Number of trials	24	24	24	24	24

Figure 44. Arable crops. Comparison of SUNDIAL-FRS and RB209 recommendations and farm practice with measured N optima.



In contrast to the vegetable trials, there was a tendency for each recommendation method to overestimate N requirement. This was particularly marked for RB209 and farm practice where rates were overestimated by more than 101 kg N ha^{-1} from the measured optima in 50% and 46% of the trials respectively. SUNDIAL-FRS predictive recommendations overestimated by the same amount in 38% of the trails, and by 21% in the retrospective recommendations. At nine sites the SUNDIAL-FRS predictive recommendations was over 100 kg N ha^{-1} more than the optimum. Using spring SMN measurements improved most of these recommendations, although five still overestimated by more than 100 kg N ha^{-1} (2/99, 3/98, 3/99, 12/99, 16/98). At two sites the recommendation was more than 100 kg N ha^{-1} less than the optimum (13/99 and 17/99). Detailed results for all trials are given in Appendix B, and these trails are discussed in more detail below.

At 2/99, 3/99 and 12/99 there was no response to applied fertiliser N, i.e. the optimum was 0 kg N ha^{-1}. Two of these sites were winter OSR, which often shows little response to fertiliser N. The RB209 and farm rates at these sites were also far too high. At 3/98 and 16/98, where high yielding winter wheats followed OSR and set-aside respectively, the SUNDIAL-FRS recommendations were far too high. These results suggest that the OSR parameters may need further development, both as a current and as a previous crop. Set-aside as a previous crop may also require further development.

At 13/99, another OSR site, the SUNDIAL-FRS retrospective recommendation was much too low. Including the spring SMN values reduced the recommendation substantially. At 17/99, winter wheat on clay, again including the spring SMN values reduced the recommendation substantially, to 208 kg N ha^{-1} less than the optimum. There was no obvious reason for this poor recommendation.

Effect of Recommendations on Marketable Yield

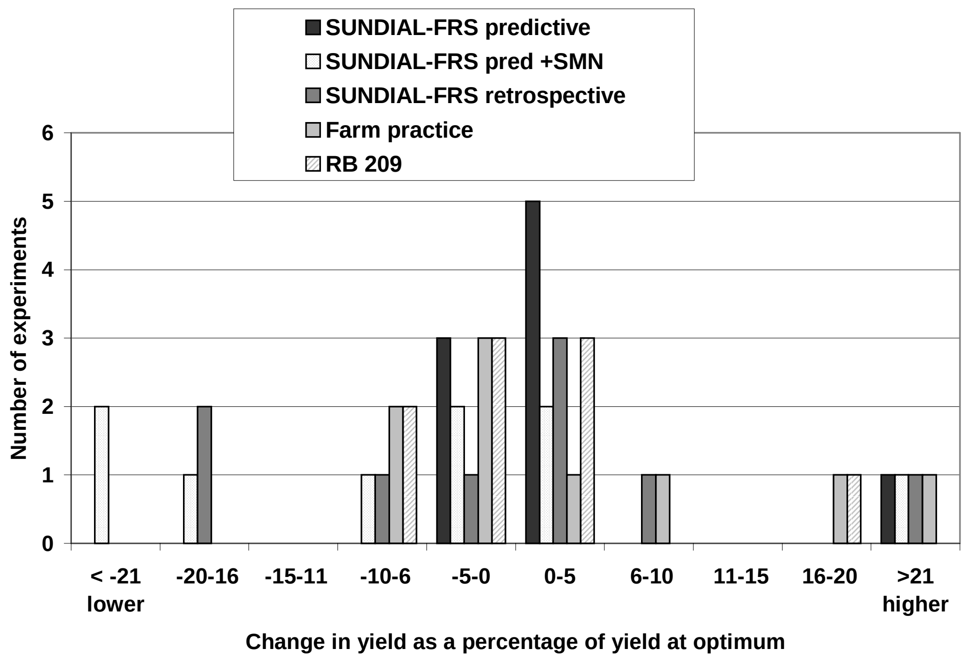
To estimate the potential effect of the recommended rates on marketable yield, yield at the recommended rate was expressed as a percentage of the calculated yield at the optimum (Table 10, Figure 45). For vegetable crops it was only possible to calculate yields at the SUNDIAL-FRS recommended rates at 9 sites. Sites where cauliflower was grown are excluded from the results.

If SUNDIAL-FRS is used predictively, the calculated yields were within 5% of the yield calculated at the optimum rate at all but one site (32/98). With RB209 and farm practice this was achieved in 67 and 44% of the trials, respectively. When spring SMN measurements were used to adjust the SUNDIAL-FRS recommendation, yields were generally reduced, and only 44% of the SUNDIAL-FRS recommendations gave calculated yields within 5% of the optimum. Again, this indicates the need for further development in the use of SMN measurements. Using actual weather and yields was of little benefit.

Table 10. Vegetable crops. Deviation of SUNDIAL-FRS, RB209 and farm practice calculated marketable yield from yield at optima. Expressed as percentage of trials.

Difference from yield at optima	SUNDIAL Predictive	SUNDIAL Predictive + SMN	SUNDIAL Retrospec-tive	Farm practice	RB209
within 5% of yield	89	44	44	44	67
within 10% of yield	89	55	66	77	89
Number of trials	9	9	9	9	9

Figure 45. Vegetable crops: Effect of SUNDIAL-FRS and RB 209 recommendations and farm practice on marketable yield.

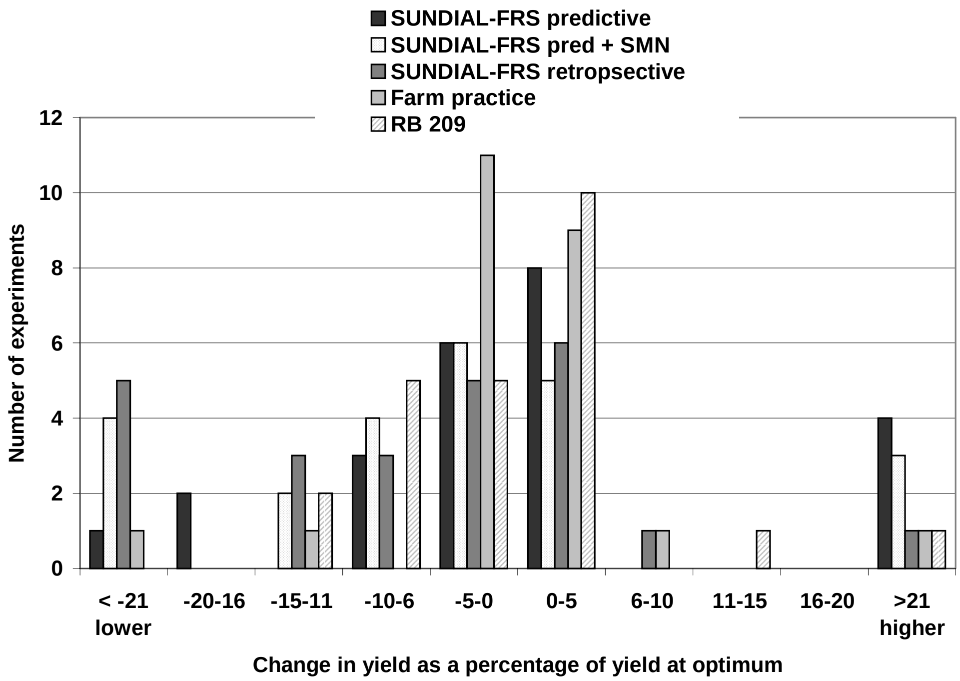


The effect of recommendations on yield of arable crops (cereals and OSR) is given in Table 11 and Figure 46. Yields could be calculated at 24 sites. Given a generally flat response to N at many sites, the yields obtained with the recommended rates and farm practice did not generally deviate by much from that calculated for the optima. Farm practice gave yields within ±5% of the optimum in 83% of the trials, with SUNDIAL-FRS used predictively and RB 209 achieving 58 and 63% respectively. When the spring SMN measurements were included, many of the SUNDIAL-FRS recommendations were reduced, and only 46% gave yields within ±5% of the optimum. Including actual weather and yields gave no further improvement.

Table 11. Arable crops. Deviation of SUNDIAL-FRS, RB209 and farm practice calculated marketable yield from yield at optima. Expressed as percentage of trials.

Difference from yield at optima	SUNDIAL Predictive	SUNDIAL Predictive + SMN	SUNDIAL Retrospec-tive	Farm practice	RB209
within 5% of yield	58	46	46	83	63
Within 10% of yield	71	63	65	87	84
Number of trials	24	24	24	24	24

Figure 46. Arable crops: Effect of SUNDIAL-FRS and RB 209 recommendations and farm practice on marketable yield.



Crop N Uptake and Soil Mineral N

Simulated and measured values were compared at each site, for the zero and maximum N rates (see Appendix B). The SUNDIAL-FRS simulations used actual weather, yields and applied, plus spring SMN measurements where available. Figures 47 and 48 show the plots of simulated vs measured crop N plus SMN at harvest for all the horticultural and arable sites respectively.

Figure 47. Horticultural Crops: SUNDIAL-FRS simulated crop N + soil mineral N plotted against measured values. The line shown is the line of perfect agreement.

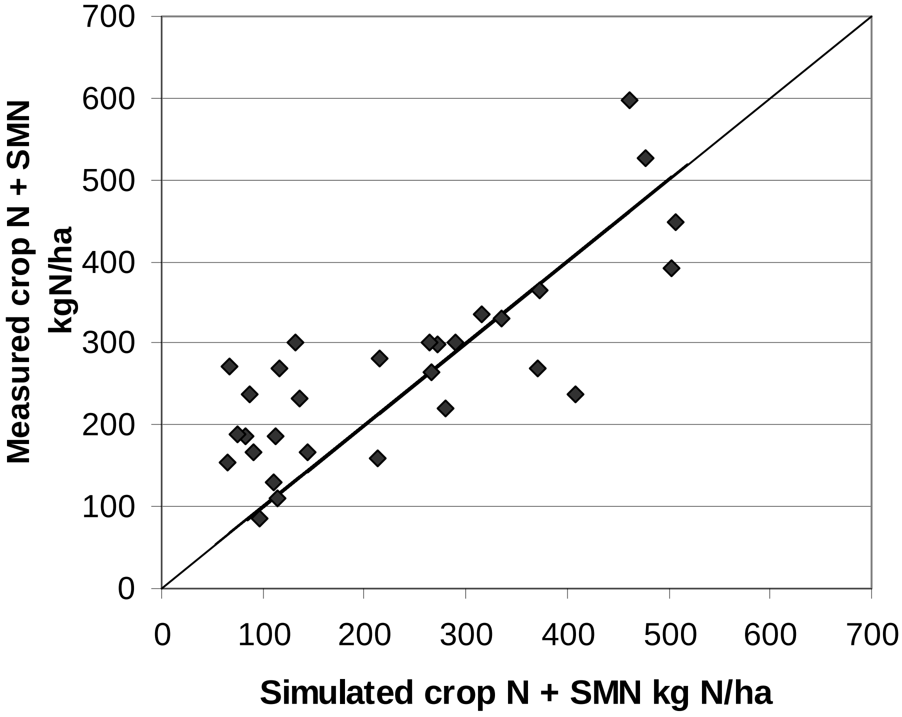


Figure 48. Arable Crops: SUNDIAL-FRS simulated crop N + soil mineral N plotted against measured values. The line shown is the line of perfect agreement.

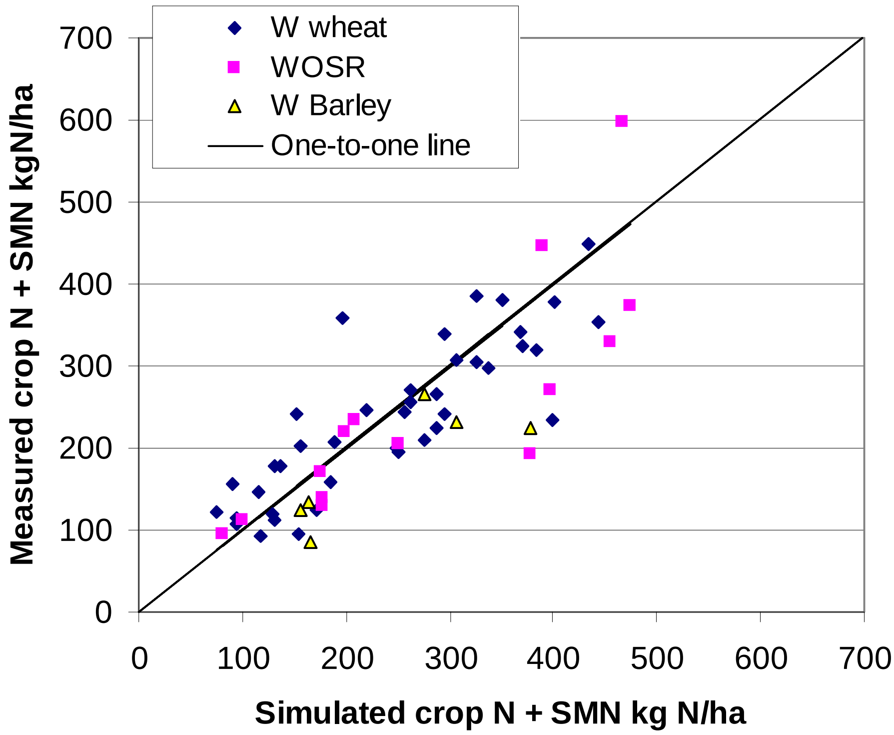


Table 12 summarises the statistical evaluation of the SUNDIAL-FRS simulations of soil mineral N + crop N uptake against measured values. The correlation between simulated and measured values is highly significant ($P<0.05$) in both horticultural and arable sites, at $r=0.79$ and $r=0.82$ respectively. The mean difference, M, indicates the level of bias in the simulations. Comparison of the Student's *t* value associated with *M* with the critical *t* value ($P<0.05$) indicates that the bias, *M*, is non-significant at arable sites (t=1.7, t_{crit}=2.0). At horticultural sites, the bias is very close to the non-significant level. The root mean squared error, *RMSE*, gives an indication of total error between simulated and measured values. $RMSE_{95}$ is the value of the *RMSE* statistic that would correspond to the 95% confidence interval in the measurements. At the horticultural sites, *RMSE* is greater than $RMSE_{95}$ (*RMSE*=35; $RMSE_{95}$=17)and so the total error is significant at $P<0.05$. At the arable sites, *RMSE* is very close to the $RMSE_{95}$ value (*RMSE*=25; $RMSE_{95}$=23) and so the total error can be considered to be non-significant at $P<0.05$. The average difference between simulated and measured values, indicated by the root mean squared value, *RMS*, is 92 kg N / ha at horticultural sites and 68 kg N / ha at arable sites. These values are surprisingly high, given the high correlation between simulated and measured values. The average difference is increased by large errors in a small number of values. This is reflected in the maximum error between measured and simulated values: 202 kg N / ha at horticultural sites and 153 kg N / ha at arable sites. Future work should focus on the sites at which high errors occur to determine whether there is some real process not included in the models or whether the measurements at these sites were erroneous.

Table 12. Measured Soil Mineral N + Crop N Uptake vs Value Simulated by SUNDIAL-FRS (statistics as described by Smith *et al*, 1996).

	Horticultural	Arable
r = Correlation coefficient	0.79	0.82
Student's *t* associated with *r*	6.91	11.11
Critical *t* value (at 5%)	2.04	2.00
M = Mean Difference (kg N / ha)	34	14
Student's *t* associated with *M*	2.1	1.7
Critical *t* value (at 5%)	2.0	2.0
RMSE = Root Mean Squared Error	35	25
$RMSE_{95}$	17	23
RMS = Root Mean Squared Deviation (kg N / ha)	92	68
Maximum Error (kg N / ha)	202	153
Number of Values	30	60

Conclusion
The overall conclusion from both the vegetable and arable sites is that, in the majority of circumstances, the use of SUNDIAL-FRS gives much the same yield as following RB209. However, SUNDIAL-FRS is more likely to recommend the correct rate of N, than RB209 or farm practice, thereby reducing fertiliser costs and wastage to the potential benefit of the environment. Using spring SMN measurements as diagnostics did not generally improve the recommendations, and was of little benefit in terms of yield. Further work is needed to develop the use of SMN as a field diagnostic. Overall, using actual weather and yield was of only small benefit. However, any potential improvements will have been hidden by the detrimental effect of using the spring SMN measurement.

3.4.3. Nitrogen-FRS Evaluation

The decision support system requires the evaluation to indicate which model should be used for each crop and on each soil type. Due to lack of response to nitrogen or the absence of a clear optimum nitrogen rate, it is not possible to use normal methods of model evaluation (such as given by Smith, *et al*, 1996) to provide this information. In a simple ranking test, the models were ranked in order of closest estimate of optimum nitrogen rate. Results were excluded from the trials where there was no clear optimum N rate. Trials showing no response to N were included, as this is a positive result, indicating no fertiliser N should be applied. The model giving the closest estimate of the optimum scored 1 point. Where the optimum was above the maximum rate included in the trial, the model recommending the highest nitrogen rate scored 1 point. Where 2 or more models gave the same result, the point was divided between them. The model was excluded from the ranking if it had been parameterised using data from the trial (e.g. SUNDIAL-FRS recommendations for cauliflowers), if it was unable to provide recommendations for that crop (e.g. there are no WELL_N recommendations for oilseed rape and no SUNDIAL-FRS recommendations for several vegetable crops) or if the simulation was under conditions for which it had not been developed (e.g. WELL_N on heavy clay soils). The total points were expressed as a percentage. Note that this test gives no indication of how good the estimate of optimum nitrogen rate is. The purpose of the test is to determine which model should be used to provide the recommendation. It does not constitute a statistical comparison of model performance. This simple test suggests SUNDIAL performs best overall in the arable sites and WELL_N performs best overall in the horticultural sites (see Table 13). This result is not a comparison of model performance, but provides a basis on which to select the default model: in the absence of further information, SUNDIAL will be used as the default model in arable sites; and WELL_N will be used as the default model in horticultural sites.

Table 13: Frequency of model showing closest match to optimum N rate

Model	Arable Crops	Horticultural Crops	Overall
SUNDIAL	33%	24%	30%
WELL_N	26%	32%	28%
RB209	15%	20%	17%
Farm Practice	26%	24%	25%

Further subdivision of the simple ranking test was used to indicate which model should be used for a particular crop or soil type (Table 14). For some crops and some soil types, this comparison was done using data at only one site, and so in no way should this be taken to be a statistical comparison. However, the comparison is useful because it provides a look-up table that can be coded into the decision support system to guide automatic model selection. As future field trials in other projects are completed, further data for evaluation will become available. Therefore, a user interface is included that allows the look-up table for automatic model selection to be altered according to future results. In addition, the user can select to manually override the automatic model selection at any time.

Table 14a: Model showing closest match to optimum N rate for a range of crops

Crop	Optimum Model
Winter Wheat	SUNDIAL / WELL_N
Winter Barley	SUNDIAL
Winter Oilseed Rape	SUNDIAL / RB209
Spring Oilseed Rape	SUNDIAL
Potatoes	SUNDIAL / RB209
Sugar Beet	SUNDIAL
Dutch White Cabbage	RB209
Savoy Cabbage	RB209
Brussels Sprouts	SUNDIAL
Cauliflower	WELL_N
Spinach	WELL_N
Red Beet	WELL_N / SUNDIAL / RB209
Calabrese	RB209
Crisp Lettuce	WELL_N
Carrot	WELL_N / SUNDIAL
Parsnip	RB209
Red Bulb Onion	RB209
Bulb Onion (sets)	WELL_N
Salad Onion	SUNDIAL
Leek	SUNDIAL
Dwarf Bean	RB209

Table 14b: Model showing closest match to optimum N rate for a range of soils

Soil	Optimum Model
Loamy Sand	SUNDIAL
Sandy Loam	SUNDIAL
Silt Loam	WELL_N
Sandy Clay Loam	SUNDIAL
Silty Clay Loam	RB209
Clay Loam	SUNDIAL
Clay	RB209
Peat	RB209

The automatic model selection is initially based on crop-type: the optimum model scoring 1, and all other models scoring 0. Where 2 models are ranked equally as the optimum, the automatic model selection passes to model preference according to soil type, again the optimum model for a given soil type scoring 1, and all other models scoring 0. Multiplication of the crop and soil score allows the optimum model with a final score of 1 to be determined.

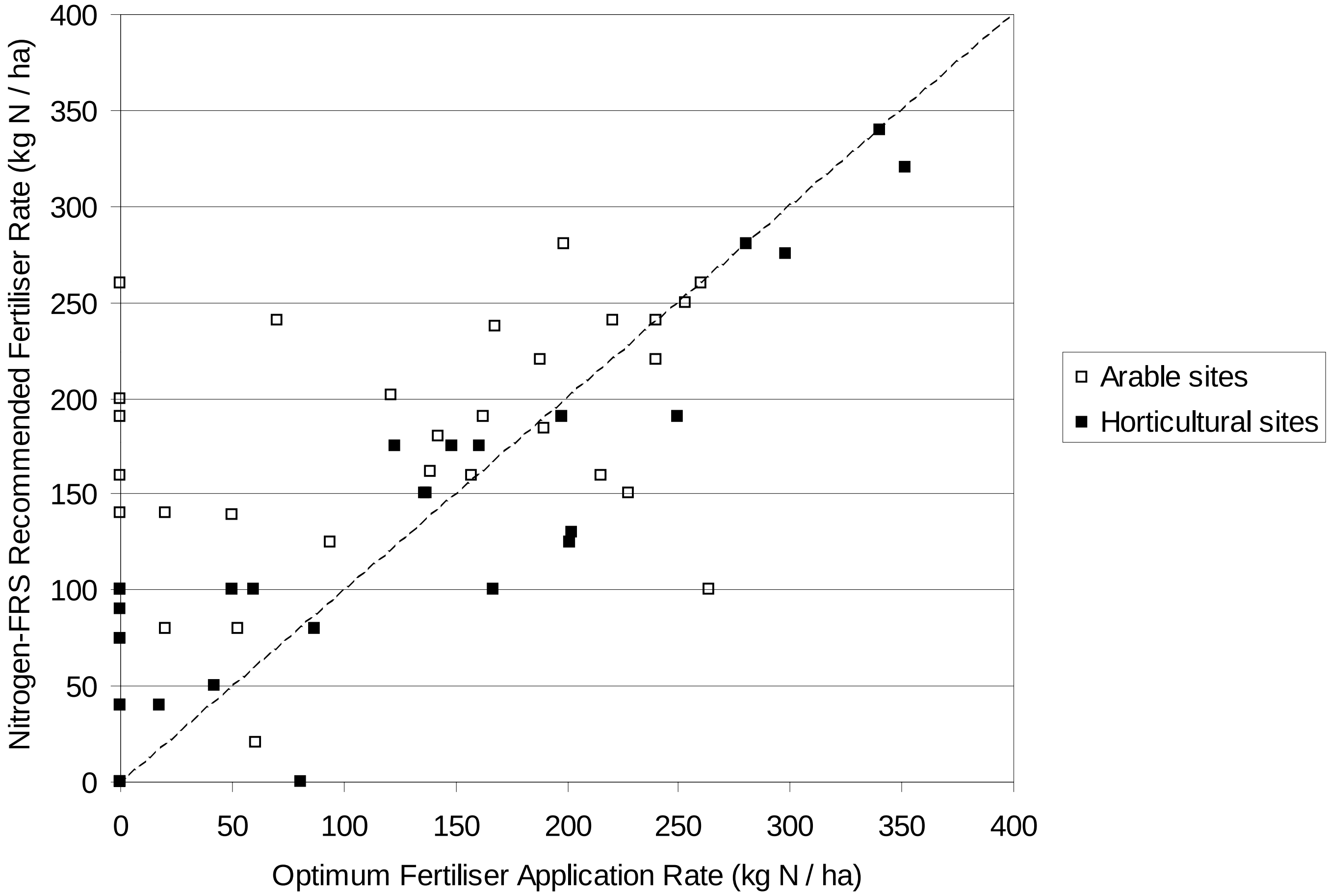
The automatic model selection procedure was used to obtain fertiliser recommendations from the combined Nitrogen–FRS. The ability of Nitrogen-FRS to predict the optimum nitrogen rate was compared to farm practice (Table 15).

Table 15. Evaluation against Optimum N Rate of Recommendations provided by Nitrogen-FRS and Farm Practice (statistics as described by Smith *et al*, 1996).

	Arable Sites		Horticultural Sites		Overall	
	Farm Practice	Nitrogen-FRS	Farm Practice	Nitrogen-FRS	Farm Practice	Nitrogen-FRS
r = Correlation coefficient	0.40	0.55	0.57	0.89	0.47	0.70
Student's *t* associated with *r*	2.58	3.83	3.22	9.38	4.08	7.39
Critical *t* value (at 5%)	2.03	2.03	2.07	2.07	2.00	2.00
M = Mean Difference (kg N / ha)	-67	-47	-35	-4	-54	-30
Student's *t* associated with *M*	-4.5	-3.4	-1.8	-0.4	-4.6	-3.1
Critical *t* value (at 5%)	2.0	2.0	2.0	2.0	2.0	2.0
RMS = Root Mean Squared Deviation (kg N / ha)	109	95	98	50	105	80
Maximum Error (kg N / ha)	255	260	215	100	255	260
Number of Values	36	36	24	24	60	60

In arable and horticultural sites, both farm practice and Nitrogen-FRS recommendations are significantly correlated to the optimum N rate, as shown by the correlation coefficient, *r* ($P < 0.05$). Nitrogen-FRS is more highly correlated to the optimum N rate than farm practice. The mean difference, *M*, indicates the bias in the error between the recommendation and the optimum N rate, and is significantly higher for farm practice than for Nitrogen-FRS. The root mean squared deviation, *RMS*, calculates the average deviation in the recommendation from the optimum N rate, and again is significantly higher for farm practice than for Nitrogen-FRS. These statistics indicate that the performance of Nitrogen-FRS is significantly better than farm practice, and show greater improvement for horticultural than arable sites. However, even for Nitrogen-FRS recommendations, the values of *RMS* range from 50 to 95 kg N / ha. The plot of recommended values against the optimum N rate (figure 49) illustrates that the high RMS values are attributable to the failure to reproduce a small number of values where the optimum N rates that occurred at 0. This is supported by the high maximum error between recommendations and the optimum N rate, suggesting that a small number of poor recommendations are increasing the apparent error. Further work is needed to simulate the processes that caused the optimum N rates to be 0.

Figure 49. Recommendations Provided by Nitrogen-FRS compared to Optimum N Rate



This novel approach has allowed us to combine all 3 recommendation systems, SUNDIAL-FRS, WELL_N and RB209 into a single fertiliser recommendation system. Different approaches are no longer competing: instead each helps the overall system to provide better recommendations. Under MAFF funding, an evaluation is currently underway of the performance of the revised RB209. If the evaluation indicates improved recommendations using revised RB209, this could also be incorporated into Nitrogen-FRS. This system allows diverse recommendation systems to be combined into one decision support system and used together to improve the overall result.

4. Conclusions

Nitrogen-FRS - Two dynamic N turnover models, SUNDIAL and WELL_N have been combined in a single package with a static model based on MAFF Reference Book 209 (MAFF, 1994). The package, referred to in this report as "Nitrogen-FRS", allows the user to manually select the model, but also has the potential to automatically set the optimum model for use under particular field conditions. The system is Windows based and fully supported by default values, allowing simulations to be run quickly and easily with minimum requirement for user inputs. If more season and site specific data on crop management, soil description, weather data or manure inputs are entered, the dynamic models have the potential to provide season and site specific N fertiliser recommendations. The system provides further support for planning N use by presenting balance sheets, graphical plots and flow charts showing changes in the N status of the soil / crop system over time. It is envisaged that the system will be made available both as a standalone and a DESSAC compatible version. This is essential if the system is to make use of the additional functionality of DESSAC, while remaining accessible to DESSAC and non-DESSAC users alike.

Database of Measurements - In order to evaluate the likely accuracy of the fertiliser recommendations and simulations of N turnover on working farms, and to identify which model should be used to simulate a particular crop, field trials were run over 2 seasons on 37 sites across the UK including a range of arable and horticultural crops. Spring and harvest soil mineral N was measured at 0-30cm, 30-60cm and 60-90cm. Whole crops were sampled at harvest and analysed for N content. A database was constructed to store the descriptions and results of the field trials, and make it readily available for future use. This was designed with a hierarchical structure, starting with site identifiers (name of farmer etc.) expanding to general site data (e.g. location, soil type and previous husbandry details), and further to incorporate data which varies over time, and finally to data collected from each experimental plot.

Nitrogen Response -These trials were planned to evaluate the performance of the SUNDIAL-FRS and WELL_N fertiliser recommendation systems. In practice, they have told us more about response to nitrogen on working farms than about the functioning of the models themselves. No response to nitrogen application was observed in 14 of the trials out of a total of 64. Several of these are due to applications of manure – sites 9/99, 15/98 and 15/99, in which case an optimum of zero is quite reasonable. At other sites there were inadvertent applications of fertiliser N to the trial (sites 19/99 and 2/98). Nitrogen uptake, where no fertiliser was applied, varied from 21 to 266 kg N ha^{-1}. This reflects inherent differences in the fertility of the soil and the period and duration of crop growth. Surprisingly there was no significant relationship between spring soil mineral nitrogen and crop nitrogen uptake on zero plots, even when only the combinable crops, or winter wheat, alone were included. This suggests that soil characteristics more closely related to soil nitrogen supply, such as the soil organic nitrogen, may also be important input data. The optimum nitrogen fertiliser application (with an estimate of its 95% confidence interval) could be determined from a linear plus exponential relationship, for only 36% (23) of the trials. There were 9 trials where no optimum could be fitted, possibly because the optimum was below the range of N rates used. In some cases, this may be due to high levels of fertiliser N and manure being used on commercial farms in previous years, where maximum productivity is paramount. It indicates an inefficient system that may be detrimental to the environment. It is particularly difficult to evaluate the performance of the models on these sites where an optimum N rate cannot be established (the optimum is zero if there is no response to N).

Shortage of Data - The models have been run assuming default soil conditions and using a maximum of five years of cropping history at the arable sites, and often only one or two years of cropping history at the horticultural sites. These limited data inputs cannot account for the changes in soil nitrogen supply that occur under a long-term high nitrogen input regime. This problem affects dynamic fertiliser recommendation systems using minimal input data in the same way as it affects static systems such as RB209. The effect is likely to be experienced by a large proportion of farmers attempting to achieve maximum productivity. High nitrogen input regimes can only be adequately described using a dynamic simulation model, driven by a suite of field diagnostics or using field records of more than 10 years. Where farmers do not have adequate long-term records, further work to develop field diagnostic measurements that can be used to drive models will be essential for future improvements in precision.

Spatial Variability – In some trials, the difficulty in determining an optimum nitrogen application rate appears to be due to spatial variability in the field. Spatial variability is an inevitable feature at some sites due to factors such as field history, underlying soil type, drainage conditions and field gradient. Methods for accounting for spatial variability in fertiliser recommendation are urgently needed. This could be done by driving the model using measures of the previous years yield combined with remotely sensed field diagnostics. In the longer term, a model including lateral movement of nitrogen due to the gradient may be beneficial. At some sites, increased precision in fertiliser applications will only be possible by developing advanced methods to describe the spatial variability of the soil.

Evaluation of Models - Evaluation at both the vegetable and arable sites indicated that the fertiliser recommendations from SUNDIAL-FRS, WELL_N and RB209 resulted in similar crop yields. However, both WELL_N and SUNDIAL-FRS gave more accurate recommendations than RB209 or farm practice, thereby reducing fertiliser costs and wastage to the potential benefit of the environment. Using spring SMN measurements as diagnostics did not generally improve the recommendations in SUNDIAL-FRS, and was of little benefit in terms of yield. Further work is needed to develop the use of SMN as a field diagnostic. Overall, using actual weather and yield was of only small benefit.

Model Improvements - The need for a number of model developments was highlighted in the evaluation process. (1) The precision with which soil nitrogen supply can be simulated would be improved by the development of links to field diagnostic measurements describing the quality and quantity of organic matter in the soil profile. A promising method is the hot KCl extraction procedure currently being investigated at IACR Rothamsted, IGER North Wyke and ADAS Gleadthorpe. (2) A module describing variable crop N uptake has been developed for SUNDIAL-FRS in earlier work. It was not implemented in the evaluated model as previous evaluations on experimental farms had not indicated the need for this extra level of complexity. However, on working farms, where fertiliser has been applied to achieve maximum possible yield for a number of years, variable uptake is a more important factor and so this module should be implemented. (3) Description of nitrogen sequestration from porous bedrock may be important in shallow soils. A new module to describe this could use the porosity of bedrock and the history of nitrogen leaching from the profile to determine the potential for nitrogen sequestration during periods of drought. (4) Where farmyard manures were applied, errors are observed associated with the timing of nitrogen mineralisation from the manure. Farmyard manures are inherently variable in nature. The farmyard manure parameters used in SUNDIAL-FRS are based on an average standard for each manure type. There is a need to develop a manure module that will allow improved description of a specific manure according to diagnostic manure measurements and information that is available to the farmer.

Evaluation of Nitrogen-FRS -When all 3 models were combined into the single package, Nitrogen-FRS, the fertiliser recommendations were significantly better than farm practice. It should be emphasised that the farmers participating in the trials were highly skilled at selecting optimum application rates. They were very familiar with the conditions on their farms and had years of experience in determining the nitrogen fertiliser rate that should be applied. As a result, farm practice was highly correlated with the observed optimum N rate. However, Nitrogen-FRS consistently provided improved recommendations over farm practice. This indicates the success of combining the 3 nitrogen recommendation systems into a single package. Different approaches to fertiliser recommendation no longer need to compete: instead each helps the overall system to provide better recommendations. Since the initiation of this project the 7th edition of RB209 has been published (MAFF, 2000). This should also be incorporated into Nitrogen-FRS, to provide a single source of the latest information for both arable and vegetable crops. This system allows diverse recommendation systems to be combined into one decision support system and used together to improve the overall result.

5. Exploitation of Results

5.1 Decision Support System

Nitrogen-FRS is due to be released during 2001. It will be distributed under licence or by subscription to pay for continued product support. The system will be available on CD or over the Internet. The Internet has the advantage of low cost distribution and rapid product upgrade. A business plan is currently being negotiated between IACR, HRI, MAFF and the partners of this project.

5.2 Database

Researchers may apply to HRI for a copy of the database and guide.

5.3 Further work

The overall objective of the work was to develop a combined fertiliser recommendation system using the existing models, SUNDIAL, WELL_N and RB209, and to demonstrate the effectiveness of the system using the results of field trials on working farms. This has been achieved, and the evaluation of the recommendations provided by the combined system, Nitrogen-FRS, show a significant improvement in accuracy over the recommendations provided by the individual models. In parallel with these developments, SUNDIAL-FRS has received 3 years additional funding from MAFF since the start of this project, and so its interfaces and facilities have advanced since this project was planned. These developments have already been incorporated in Nitrogen-FRS but corresponding upgrades to the interfaces for WELL_N have yet to be made. As a result the consistency and effectiveness of the system would be improved if the interfaces to WELL_N were updated to match the developments already made for SUNDIAL-FRS. Potential areas for improvement are outlined below:

1. *Weather Generation*. SUNDIAL-FRS can obtain default weather data for any given region using the internal weather generator, ETCETERA. The weather data needed to run WELL_N is different to that needed to run SUNDIAL-FRS. Recommendations from Nitrogen-FRS would be made more consistent by extending the weather generator used by SUNDIAL to provide data for WELL_N.

2. *Presentation of Results*. The recommended fertiliser application rate is clearly presented by the system for SUNDIAL, WELL_N and RB209. However, both SUNDIAL and WELL_N produce additional data relating to the soil nitrogen and carbon status, nitrogen losses from the soil, plant growth, soil water contents, etc. Because the theoretical basis of SUNDIAL and WELL_N is not the same, the types of results produced by the two models differ. Work has been completed to create graphical interfaces to present the results produced by SUNDIAL but the results produced by WELL_N have yet to be fully exploited. The range of information provided by Nitrogen-FRS would be increased by further development of the result screens for WELL_N.

3. *Access to Model Parameters*. Work has been completed to provide access to the parameters used to drive SUNDIAL through the graphical user interface. This helps users to understand what information is being used to generate a particular recommendation, and allows the user to enter more site specific input parameters. For instance, if the farmer uses a fertiliser blend that is not included in the list of fertiliser types, alterations can be made to the proportions of nitrogen compounds in the fertiliser used. The model parameters used by WELL_N differ from those used by SUNDIAL. The site specificity of Nitrogen-FRS would therefore be improved by developing similar parameter screens for WELL_N.

4. *Extending the system to include the latest version of RB209.* Since the initiation of this project a new version of MAFF Reference Book 209 (UK National Fertiliser Recommendations) has been published (MAFF, 2000). Incorporation of these recommendations within Nitrogen-FRS would provide a single source of the latest information for both arable and vegetable crops.

6. Glossary

Crop Nitrogen Offtake: Nitrogen removed from the field in the crop.

Crop Nitrogen Uptake: Total nitrogen taken up by the growing plant, including that recycled to the soil before harvest.

Decision Support System: a computerised system to provide information to support complex decision making processes.

Dynamic Simulation Model: A computer based model that recalculates the state of the system throughout the simulation, according to specific climate and soil conditions.

Denitrification: loss of nitrogen containing gas (N_2 and N_2O) by reduction of ionic oxides nitrate (NO_3^-) and nitrite (NO_2^-)

Immobilisation: the transformation of nitrogen from plant available forms in the soil to plant unavailable soil organic matter by biological and chemical processes.

Leaching: loss of nitrogen as soluble nitrate in drainage water.

Mineralisation: the transformation of nitrogen from soil organic matter to plant available forms by biological and chemical degradation processes.

Nitrification: the transformation of ammonium (NH_4^+) to nitrate (NO_3) by micro-organisms within the soil

Senescence: the loss of nitrogen from the plant after anthesis by leaf fall.

Static Simulation Model: a one-stage calculation that takes no account of progress of the soil/crop system with time.

Strawing: the covering of carrots with straw (c.40 t/ha) to protect the crop from frost during overwinter storage in the ground.

Volatilisation: the loss of ammonium nitrogen (NH_4^+-N) from the plant or soil as gaseous ammonia (NH_3).

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