General enquiries on this form should be made to:
Defra, Science Directorate, Management Support and Finance Team,
Telephone No. 020 7238 1612
E-mail: research.competitions@defra.gsi.gov.uk

SID 5 Research Project Final Report

- **Note**

  In line with the Freedom of Information Act 2000, Defra aims to place the results of its completed research projects in the public domain wherever possible. The SID 5 (Research Project Final Report) is designed to capture the information on the results and outputs of Defra-funded research in a format that is easily publishable through the Defra website. A SID 5 must be completed for all projects.

  A SID 5A form must be completed where a project is paid on a monthly basis or against quarterly invoices. No SID 5A is required where payments are made at milestone points. When a SID 5A is required, no SID 5 form will be accepted without the accompanying SID 5A.

- This form is in Word format and the boxes may be expanded or reduced, as appropriate.

- **ACCESS TO INFORMATION**

  The information collected on this form will be stored electronically and may be sent to any part of Defra, or to individual researchers or organisations outside Defra for the purposes of reviewing the project. Defra may also disclose the information to any outside organisation acting as an agent authorised by Defra to process final research reports on its behalf. Defra intends to publish this form on its website, unless there are strong reasons not to, which fully comply with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

  Defra may be required to release information, including personal data and commercial information, on request under the Environmental Information Regulations or the Freedom of Information Act 2000. However, Defra will not permit any unwarranted breach of confidentiality or act in contravention of its obligations under the Data Protection Act 1998. Defra or its appointed agents may use the name, address or other details on your form to contact you in connection with occasional customer research aimed at improving the processes through which Defra works with its contractors.

Project identification

1. Defra Project code: OF0316
2. Project title: The development of improved guidance on the use of fertility building crops in organic farming
3. Contractor organisation(s): ADAS
   Woodthorne
   Wergs Road
   Wolverhampton
   WV6 8QT
4. Total Defra project costs: £ 379919
5. Project: start date................. 01 May 2002
   end date.................. 28 February 2006

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so. ....YES ☒ NO ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.
Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.
In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Fertility building crops are a key component of organic rotations where they help to provide nitrogen required for optimal crop performance. It is important that rotations and managements are planned which optimise the capture and use of this nitrogen. Some estimates are available of the nitrogen production from fertility building crops, but there was a need to produce a more comprehensive assessment of likely nitrogen fixation, release and availability under different circumstances. Thus the overall aim of the study was to provide guidelines to enable organic farmers to better estimate the nitrogen supply to a rotation following fertility building crops. This was done by a mix of literature review, empirical measurements, model development and farmer participation.

The detailed **objectives** were:

1. To produce a literature review summarising the current knowledge on N capture and supply and secondary effects (e.g.pest/disease implications) following fertility building crops.
2. To engage the organic farming community to ensure that the most relevant issues were addressed within the project.
3. To produce an advisory leaflet summarising practical advice arising from the literature review.
4. To conduct field experiments to supply supplementary information that was required to develop a model for quantifying N supply from fertility building crops.
5. To develop a model for quantifying N supply from fertility building crops in organic systems.
6. To make on-farm measurements to validate this model.
7. To synthesise this information into practical advice for the industry in the form of a booklet on fertility building crops.

The study was split into a number of **interlinked work-strands**: Literature review, Field experiments, On-farm monitoring, Industry engagement, Fertility building crops (FBC) model, Advisory leaflet and Guidelines booklet.

The **literature Review** (Objective 1) was an essential first activity as it helped to guide the experimental programme (in terms of focus, techniques and approaches), avoided unnecessary replication of experimental work and provided an immediate synthesis of available information for the Industry (see Objective 3). The review also formed the basis of Objectives 5 and 7. Over 1000 references were assessed to produce a summary of the current state of knowledge in the following topic areas:

- Nitrogen build-up, release and availability
- Crops, pests, diseases and rotational issues

The structure of the review exemplifies how the project tried to quantify N supply from fertility building crops, i.e. by separating the management process into N capture and N release. Many factors affect both of these processes. The conclusions that we were able to draw from the large body of work were able to serve three puposes:

- Form the basis of advisory literature
- Inform the research programme
- Inform the FBC model development

Industry engagement (Objective 2) was a key component of the study and there was good liaison with the organic farming industry at the beginning and throughout the duration of the project. This liaison was co-ordinated by The Organic Studies Centre at Duchy College in the South West, and by Abacus Organic Services Ltd in the East and North East. Feedback from producers was elicited throughout the project to help ensure that the industry's requirements were met, notably with respect to trials (Objective 4) and advisory material (Objectives 3 and 7). Some of the farmers were also involved in on-farm monitoring, supplying fields which were used to take measurements of N supply from selected rotations (Objective 6). In all, the project findings were promoted at a total of 20 farmer meetings, and 7 articles were published in the popular press.

A key early deliverable from the project was a summary **advisory leaflet** (Objective 3) based on the literature review. The draft leaflet addressed the main practical issues of fertility building crops and was presented at farmer meetings. Feedback on the leaflet was invited at these meetings and issues raised were addressed in the final version which is available on the project website and as an attachment to this report.

The main **field experiment** (Objective 4) was designed to examine the effect of soil-N status on the quantity of N fixed and the impact on N-fixation of returning plant residues to the growing crop in cutting/mulching managements. The original project was extended with approval from Defra during 2004 to include measurements on the amount of N released following destruction of these legume management plots. As a result of industry feedback (see Objective 2), demonstration plots were also set up to look at novel legumes.

The legume management data showed that in terms of fixation, maximum N yield (as measured by N offtake) occurred in the mulched grass/clover sward. But, using the measured data, separate estimates for the effect of mulching on N fixation showed it caused a reduction of between 9 and 61 kg N ha^{-1}. In the presence of FYM there appears to have been an interaction with mulching which was sufficient to depress N fixation by an amount roughly equal to the amount of N gained from the amendment. Availability of fixed N is also important and the amount of N released following destruction of the experimental swards was assessed by measuring the uptake of nitrogen in the following ryegrass crop. Irrespective of management history, N offtake was higher at the first cut where there had been a history of FYM applications. There was positive relationship between N capture (as measured by N offtake) and total N supply (as measured by SMN and N in crop residues) but the impact of the individual N supply components on this relationship varied between sites and between cuts..

Recommendations to organic farmers from this part of the work, are therefore to cut and remove herbage during the fertility building phase. This may be difficult for non-livestock enterprises and care needs to be taken that the mulch does not kill out the receiving crop. Application of organic manures to legumes should also be avoided if the maximum amount of atmospheric N is to be fixed.

On-farm monitoring (Objective 6) included measurements of N accumulation (as soil and crop N) and subsequent N supply (as soil N) in 12 commercially farmed fields covering a range of soil types and rotations. The data collected were used in the FBC model (Objective 5) and highlighted the high proportion of nitrogen held within the root component of the fertility building crops.

The **fertility-building crops model** (Objective 5) is a spreadsheet-based calculation system for estimating available N in organic rotations based on N accumulation under fertility building crops, its subsequent release and associated losses. It is based on information from the literature review (Objective 1), other soil nitrogen models, results from the field trials (Objective 4) and on-farm monitoring (Objective 6). It was recognised in the original proposal that it would not be possible within the timescale of the present project to deliver a fully functional and validated model that was suitable for release to the industry. Accordingly, a much-simplified version of the model is presented as a flow diagram in the final deliverable from the project the **Guidelines booklet** (Objective 7).

Implications of the findings

The results help Defra meet its policy objectives, in supporting organic farming and in facilitating better N utilisation within the rotation, thereby helping to minimise losses of N to the wider environment.

The project outputs give practical advice to organic farmers and growers. The results provide a better understanding of nitrogen accumulation under fertility building crops and its subsequent release. This is important in terms of rotation planning where it can help to maximise the yield potential of high value crops, and hence improve overall biological and economic sustainability. Confirmation that high soil nitrogen (either from application of FYM or mulch) reduces fixation is a significant finding.

With further development, the FBC model has the potential to be used as a fully operational Decision Support System, either as a stand-alone package, or via a website.

The information on fixation, soil N build-up and subsequent release under different legumes is also of value to non-organic farmers. They face escalating input costs and environmental restrictions, and are looking for ways of reducing reliance on purchased synthetic fertilisers.

The results may be of use in improving the soil nitrogen supply estimates in Defra's fertiliser recommendations reference book (RB209).

Future Work

Feedback from farmers, and the results from the novel legume demonstration indicate that more work is needed on the less well-understood legume species. This work might be appropriate for LINK funding.

There is also a need to understand the extent to which slurry applications, with higher levels of available N than the FYM applied in this study, can adversely affect N fixation, since the application of liquid manures to fertility-building crops is common practice in organic dairy farming.

There are opportunities to extend the model to cover a wider range of cropping situations. Also there was considerable interest and enthusiasm for the FBC model at the farmers' meetings and a clearly expressed desire to have it made available to the industry. This would need further work to make it more suitable as a DSS for farmers, either as a stand-alone package or via the website.

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1. INTRODUCTION

Fertility building crops and green manures are key components of organic rotations. They are usually leguminous crops that fix atmospheric nitrogen (N) to provide a net import of N into the rotation. Management options for these crops are many, including choice of species and cultivar; length of growing period within the rotation; rotational position and management of foliage (cutting and exporting, cutting and mulching, grazing or combinations of these).

A major objective in the use of fertility building crops (including green manures) is to provide the N required for optimal performance of the subsequent exploitative crops in the rotation. Nitrogen is usually the limiting nutrient in organic systems, particularly in the later stages of the rotation as the N supply from fertility building crops declines. If organic farmers are to optimise the use of this nutrient, they require a reliable estimate of the amount of N available and its pattern of release. Note that there are two aspects: ‘accumulation’ (also referred to as capture) and ‘use’ (for crop growth) of N. All of the factors listed above will affect the amount of N fixed during the fertility building phase and thus influence the amount of N that has been accumulated. Efficient use of that captured N by the following crops relies on management practices and cropping patterns that make best use of the N as it is released by mineralisation of the residues. Practices that match uptake to patterns of mineralisation will optimise crop N uptake and minimise losses of N to the wider environment.

Estimates are available of the N accumulated by fertility building crops. Recent literature reviews have been completed as a part of Defra-funded projects OF0164 and OF0178. These essentially concluded that numerous empirical studies have measured N fixation by soil fertility building crops and reported a wide range of values. The often quoted Wood [1] suggests fixation values of 5-445 kg N ha^{-1} yr^{-1} for grass/clover leys under UK conditions, but removing ‘outliers’ narrows this to 100-200 kg N ha^{-1} yr^{-1}, which is still a large variation. Lucerne has been estimated to fix about 500 kg N ha^{-1} yr^{-1} [2]. Whereas clovers typically obtain over 90% of their N through fixation, grain legumes, such as peas and beans, have lower fixation rates and often depend on the soil for about 50% of their N requirements [3]. Annual fixation by pea crops was estimated to be about 100-250 kg N ha^{-1} in the Netherlands [4] and 135 kg N ha^{-1} in the UK [5].

However, it is clear that numerous factors can affect the processes of N accumulation, release and subsequent recovery. Species has an obvious and large effect [6]. Cultivar also affects N fixation. There are practical considerations also, such as crop yield, the rate of establishment of the legume, its spatial distribution and its persistence. Because fixation is a symbiotic relationship between the legume and microbe, environmental factors also play a part. The effects of pH, phosphorus status and other soil macro- and micro-nutrients have been reviewed by Hartwig & Soussana [7].

A key factor influencing fixation is the supply of soil mineral N. This is a complex relationship [8, 9] but fixation generally declines with increasing soil mineral N content. Thus, fixation will be greatest in soils of low N-status while practices that encourage high levels of mineral N in the soil will inhibit fixation.

Understanding the processes involved is much simpler for an annual legume which is grown and incorporated into the soil at the end of the growing season than for longer-term clover or grass/clover leys where fixation, losses and recycling of the fixed N occur over a number of years. This complexity is increased where the ley is grazed rather than cut. The quantity of N fixed will also be affected by pests and diseases where these affect the performance of the legume. The choice of legume and its management will in turn influence the occurrence of pests and diseases affecting subsequent crops in the rotation.

Currently, there is no advisory system available for determining N accumulation under fertility building crops that incorporates these many variables. Process-based models (e.g. 10, 11, 12) are useful for understanding N flows in grass/clover swards but are less useful for predicting the amount of N fixed. They are generally confined to descriptions of grass/clover swards and are not sufficiently flexible to handle the different managements likely to occur on organic farms. Simpler, descriptive models such as described by Korsaeth & Eltun [13] and Kristensen et al. [14] may be more useful for predicting fixation under different conditions. The former includes legumes other than mixed grass/clover swards, though not all those commonly found in organic rotations. Carberry *et al*. [15] describe the APSIM model for N flows through seed legumes, but this does not include many legumes suitable for UK conditions.

Conversely, much is already known about the process of mineralisation of organic materials when incorporated in to soils and this has been developed into a number of models. The rate of decomposition is determined by the composition and structure of the residues, modified by interactions with soil texture and climate. Several models (e.g. SUNDIAL, WELL-N, DAISY) can estimate N mineralisation and the fate of this N with some accuracy. Though valuable as research tools, existing forms of these models are generally too complex for use as an on-farm advisory tool.

Few models combine the two components of N accumulation and subsequent release through mineralisation. Consequently, current guidance is very broad and often of insufficient detail to provide robust advice to growers. A better understanding of both components would assist organic growers and have the following advantages:

- Greater awareness of the factors affecting N accumulation and N loss, and the practical management factors affecting these processes.
- Greater ability to develop sustainable rotations, matching N supply to N requirements for the rotation.
- Increased scope for adopting novel or more innovative rotations.

Thus, the overall aim of the study was to provide guidelines to enable organic farmers to better estimate the nitrogen supply to a rotation following fertility building crops. This was done by a mix of literature review, empirical measurements, model development and farmer participation.

2. OBJECTIVES

1. To produce a literature review summarising the current knowledge on N capture and supply and secondary effects (e.g. pest/disease implications) following fertility building crops.
2. To engage the organic farming community to ensure that the most relevant issues were addressed within the project.
3. To produce an advisory leaflet summarising practical advice arising from the literature review.
4. To conduct field experiments to supply supplementary information that was required to develop a model for quantifying N supply from fertility building crops.
5. To develop a model for quantifying N supply from fertility building crops in organic systems.
6. To make on-farm measurements to validate this model.
7. To synthesise this information into practical advice for the industry in the form of a booklet on fertility building crops.

3. APPROACHES

The study was split into a number of interlinked work-strands:

3.1. Literature review (Objective 1)

This was an essential first activity as it guided the experimental programme (in terms of focus, techniques and approaches), avoided unnecessary replication of previous experimental work and provided an immediate synthesis of available information for the Industry (Objective 3). The review also formed the basis of completing Objectives 5 and 7. In addition to N supply effects, the review also considered the secondary effects of fertility building crops and related managements on factors such as the occurrence of pests and diseases in organic systems.

3.2. Industry engagement (Objective 2)

A key component of the project was the involvement of organic farmers and growers at the beginning, and throughout the project. This liaison was co-ordinated by The Organic Studies Centre at Duchy College in the South West, and by Abacus Organic Services Ltd in the East and North East. Feedback from producers was elicited throughout the project to help ensure that the industry's requirements were met, notably with respect to experiments (Objective 4) and advisory material (Objectives 3 and 7). Some of the farmers were also involved in on-farm monitoring, supplying fields which were used to take measurements of N supply from selected rotations (Objective 6).

3.3. Advisory leaflet (Objective 3)

A key early deliverable from the project was a summary advisory leaflet based on the literature review. The draft leaflet addressed the main practical issues of fertility building crops and was presented at farmer meetings. Feedback on the leaflet was invited at these meetings and issues raised were addressed in the final version.

3.4. Field experiments (Objective 4)

The main field experiment was designed to examine the effect of soil-N status on the quantity of N fixed and the impact on N-fixation of returning plant residues to the growing crop in cutting/mulching managements. The literature review (Objective 1) highlighted this as a priority topic for new information. The original project was extended with approval from Defra during 2004 to include measurements on the amount of N released following destruction of these legume management plots. As a result of industry feedback (Objective 2), demonstration plots were also set up to investigate 'novel' legumes.

3.5. Fertility Building Crops (FBC) model (Objective 5)

The FBC model is a spreadsheet-based calculation system for estimating available N in organic rotations based on N accumulation under fertility building crops, its subsequent release and associated losses. It is based on information from the literature review (Objective 1), other soil nitrogen models, results from the field trials (Objective 4) and on-farm monitoring (Objective 6). It was recognised in the original proposal that it would not be possible within the timescale of the present project to deliver a fully functional and validated model that was suitable for release to the industry. Accordingly, a much-simplified version of the model is presented as a flow chart in the Guidelines Booklet (Objective 7).

3.6. On-farm monitoring (Objective 6)

Measurements of N accumulation (as soil and crop N) and subsequent N supply (as soil N) were made in 12 commercially farmed fields covering a range of soil types and rotations. The data collected were used in the FBC model (Objective 5).

3.7. Guidelines booklet (Objective 7)

The final deliverable from the project was a more detailed 'advisory' booklet ready for publishing. Feedback on the draft booklet was obtained from the industry and Defra and the final draft version has been produced (Annex to this report).

4. RESULTS AND DISCUSSION

4.1. Literature Review (Objective 1)

Over 1000 references were assessed to produce a summary of the current state of knowledge in the following topic areas:

- Nitrogen accumulation, release and availability
- Crops, pests, diseases and rotational issues

The structure of the review exemplifies how the project tried to quantify N supply from fertility building crops, i.e. by separating the processes into N accumulation in the build-up phase and subsequent N availability to crops in the release phase (Figure 1). Many factors affect both of these processes.

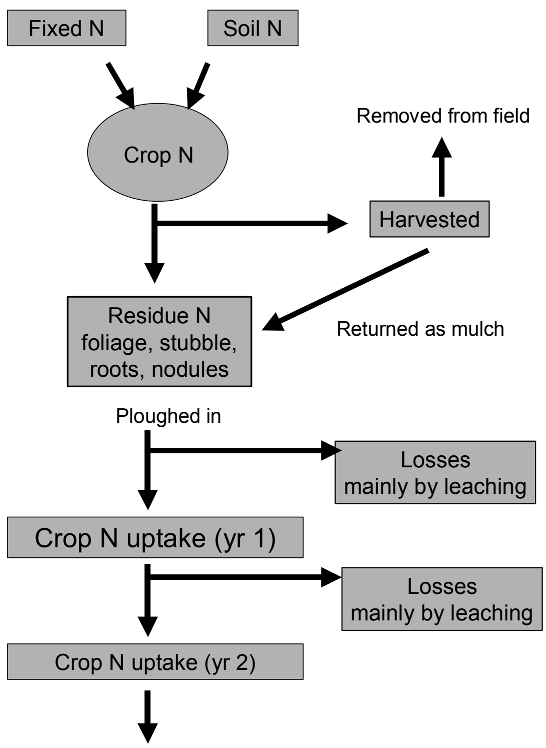


Figure 1. Diagram representing the N accumulation and release by fertility building crops.

The report structure was as follows:

1. Executive summary
2. Introduction
3. Fertility-building crops in rotations
4. How much N is captured?
5. The influence of management
6. Use of models to estimate N-fixation
7. Utilising N from fertility-building crops
8. Rotational aspects
9. Conclusions
10. Bibliography

One of the key findings of the review was the large variability in both fixed N and N remaining after removal from the field in harvested crops (Figure 2).

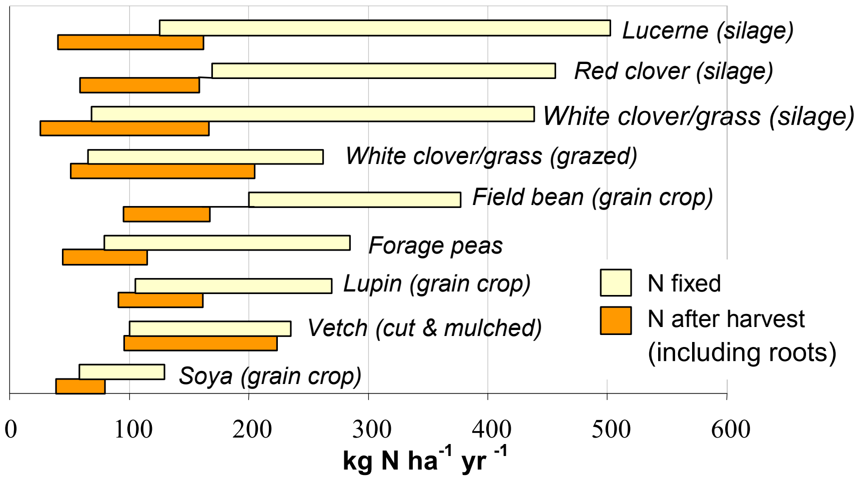


Figure 2. Ranges for quantities of N fixed and remaining after harvest of a range of legume species.

The review was presented as a written report to Defra, and it was also made widely available by posting it on the project website. The review also formed the basis of the advisory leaflet for farmers and various press articles and presentations, including a 2004 BGS/AAB/COR conference paper. A copy of the review is provided as a separate annex to this report.

4.2. Industry Engagement (Objective 2)

The first step was to discuss issues of fertility building crops with organic farmers at the outset to ensure that the most relevant issues were addressed in the project. Three meetings were held across the country (South West, North and East) during summer 2002. These workshops were the basis for discussions on farmers' needs for information on fertility building crops.

Lack of technical information and advice for organic producers was felt to be a major problem by many of the farmers present. Although priorities, especially with respect to crop management, were naturally different between arable and livestock producers, there was considerable agreement, and two common overall themes were:

- Effect of choice and management of legumes on N fixation, accumulation and release
- Interactions with weeds, nutrients, pests or diseases

A website was established to provide a focal point for information about the project (www.organicsoilfertility.co.uk) (Figure 3). Project results, reports and topical items were posted on the site.

Following the literature review (Objective 1, Annex 1), an advisory leaflet (Objective 3, Annex 2) was prepared and a draft presented at three further workshops in March 2003. Useful comments were received and the revised edition was posted on the website. A copy was made available to Defra, and it was promoted in the organic farming press and at various farmer meetings.

Two on-farm meetings (ADAS High Mowthorpe and Duchy College, Cornwall) were held in July 2003 to demonstrate progress with the field experiments and to report on preliminary results. The novel legume plots (see below) generated a great deal of interest. Information and photographs were posted on the project website.

Two meetings (ADAS Boxworth and Bodmin, Cornwall) were held in March 2005 to report and discuss progress with the FBC model. A paper-based flow chart calculator, which was developed from the model, was demonstrated at the meetings. Farmer feedback on its ease of use and value was very positive.

One of the final stages of the project was to present the draft of the Guidelines booklet (Objective 7: Annex 3) and to demonstrate the FBC model. This was done at two meetings (Midlands and South West) early in 2006.

Figure 3. Screenshot of the project website, which acted as a focus for disseminating results from the project.

4.3. Field Experiments

4.3.1. Legume management (Objective 4)

The main field experiment started in autumn 2002 at two sites, IGER North Wyke (SW) and ADAS High Mowthorpe (NE) to examine the effects of soil N supply and cutting and mulching of fertility building crops, on N fixation, build-up and release. It was decided that these were priority topics for research following the literature review. The hypothesis that we tested was that any management factor that increased soil mineral N supply to the legume (e.g. manure application, or cutting and mulching) would decrease the N fixation capacity of the legume. Thus, this would have adverse impacts on N inputs to the farm rotation. The experiment design was specifically developed to separate out the effects of N supply from fixation and other sources.

Site Details and Management

The SW site was on a well drained, reddish gravely loamy soil over Permian breccia from the Crediton Series, a typical brown earth (FAO dystric or eutric cambisol, USDA dystrochrept or eutrochrept). The site was previously under grass/white clover which had not been grazed for at least 5 years, but had a break of one year for a maize crop during that period. The NE site was on a well drained, stony calcareous silty soil over litho skeletal chalk from the Panholes Series, a typical brown earth (FAO calcic cambisol, USDA eutrochrept). The site had previously been spring barley undersown with red clover.

At both sites, the existing grass/clover swards were incorporated by ploughing, followed by further cultivations, and then rolled to produce a fine seed bed. Forty eight plots at each site (1.5 x 10 m at SW site and 3 x 12 m at the NW site) were prepared for planting in autumn 2002, either with, or without farmyard manure (FYM) incorporated into the seed bed (24 plots of each) and calculated to supply 170 kg total N ha^{-1}. At the NE site, the FYM was not actively composted, but taken from an uncovered heap, which was about 4 months old. At the SW site, composted manure was used. It had been turned three times and then stored for about 2 years under cover. The source of manure at both sites was from straw-bedded beef cattle, fed on silage and concentrates. It had total N contents of *c.* 7 and 6 kg total N t^{-1} FYM at the SW and NE sites, respectively. Both types of FYM contained *c.* 3.5 kg t^{-1} P_2O_5 and 8.0 kg t^{-1} K_2O and both sites had soil indices for available P and K that suggested further additions of P and K would not produce yield responses. The FYM used at the NE site contained some NH_4^+-N (*c.* 7% of the total N content), but the composted FYM applied to the SW site had negligible amounts.

The treatments were randomised, and half the plots were sown with red clover (*Trifolium pratense* L., cv. Merviot), and the other half with perennial ryegrass (*Lolium perenne* L.). Whereas the sown ryegrass plots at the SW site remained relatively weed-free, the clover plots included a high proportion of grasses (including some ryegrass) which regenerated from the existing seed bank. As the plots were to be managed organically, no herbicides were used, and therefore these plots were effectively red clover/grass mixed swards. For consistency, ryegrass was also sown into the red clover plots at the NE site.

The experiment layout was a split-plot design with fertility level (with and without manure) on main plots and legume management on sub plots. The sub plot treatments were:

A: Red clover/grass mixture (herbage cut and removed)
B: Ryegrass only (herbage cut and removed)
C: Red clover/grass mixture (herbage cut and returned to plot as mulch)
D: Ryegrass only (herbage cut and removed; herbage from treatment *A* spread onto this plot as mulch)

There were six replicates.

Treatments B and D acted as reference plots for treatments A and C, respectively, providing a measure of the N supply from the soil and litter in the absence of N fixation. The sub-plot treatments were randomised independently within each main treatment. Data were analysed as a split plot design using ANOVA within the GENSTAT statistical package. The two sites were analysed independently.

At both sites, the swards were cut using small-plot harvesters (*Haldrup* at the SW and *Lundell* at the NE sites) four times during each of the two growing seasons of 2003-4, except in 2004 when only three cuts were made at the NE site. To control annual weeds, an early-season cut was taken in 2003 from both sites and the herbage was removed. In the remaining harvests of 2003 and 2004, treatments *C* and *D* were mulched, as described below.

The cut herbage to be returned to the plots was spread out to dry partially and then the plots were mown again, allowing the cuttings to fall on the sward as a fine mulch. (This operation was not needed at the NE site where the Lundell mower chopped the mulch sufficiently in the first pass.) Fresh yield was determined after each cut and sub-samples from all plots were taken to determine dry weight yield and total N content.

The experiment was continued over two growing seasons to follow changes associated with increasing differences in soil fertility brought about by the different treatments. A second application of manure was added in autumn 2003 as a top dressing to the FYM-treated plots at both sites, either as composted FYM (turned three times and stored for one year after mucking out, SW site) or non-composted manure (NE site), supplying a further 170 kg total N ha^{-1}.

In spring 2005, the plots were ploughed and re-sown with ryegrass. The release of N was monitored throughout the 2005 season. Ryegrass is not a normal crop for this fertility depleting phase of an arable rotation, but was chosen as the best test crop to estimate N supply as it has a continual uptake of N.

<u>Assessments</u>

Build-up phase:

- Soil mineral N (SMN) (0-30 cm soil depth), determined each autumn
- Potentially available N using hot KCl (0-30 cm), determined at the end of experiment
- Fresh yield of herbage per unit area, dry matter and N content at each harvest
- Fractionation of soil and crop at the end of years 1 and 2 and analysis of N% in the fractions

Release phase:

- Soil mineral N (SMN) (0-30 cm), determined prior to ploughing-in, and in the autumn
- Fractionation of soil and crop prior to ploughing-in, and analysis of N% in the fractions
- Potentially available N using hot KCl (0-30 cm), determined after germination of ryegrass
- Fresh yield of herbage per unit area, dry matter and N content at each harvest

Build-up Phase

The mean content of mineral N in the upper soil profile (0-30 cm) at the start of the experiment in autumn 2002 was 52 and 62 kg N ha^{-1} at the SW and NE sites respectively. At the end of the two year build-up phase (autumn 2004), the upper profile had been depleted in the free draining soil at the SW site to 11 and 9 kg N ha^{-1} (averaged across all treatments) with and without FYM, respectively. At the NE site, mineral N increased significantly in the clover mulched treatments ($P<0.05$). This gave rise to an overall increased mean of 80 kg N ha^{-1} where FYM was supplied ($P=0.055$), but remained at 62 kg N ha^{-1} where no FYM was applied. Thus, the relatively younger FYM (stored for 4 months) was able to supply some mineral N, whereas the older FYM (SW site, stored for 24 months) was less effective.

The amounts of N remaining in the unharvested organic fractions at the end of the build-up phase (herbage re-growth, above-ground stubble and litter and macro-organic matter, which includes dead fibrous materials in a state of partial decomposition and roots, but not living materials) are shown in Figure 4 and ranged from c. 100-200 kg N ha^{-1} at the SW site and from 50-150 kg N ha^{-1} at the NE site. Even though the NE site was high yielding, there was less unharvested herbage at this site because of poorer re-growth following the final cut which was taken three weeks later than the last cut at the SW site. However, the main difference between the two sites was in the amount of N in the macro-organic fraction. For the grass treatments B and D, the amounts were similar at both sites; macro-organic N was consistently less in the manured grass plots, BM and DM compared with B and D, and lower in the unmulched grass plots, B and BM compared with D and DM, respectively, but these differences were not significant. For the clover treatments A and C, the amount of macro-organic N was much less at the NE site. This was due partly to the gradual decline in clover in the mulched plots (from 49 to 28 % between 1st and 3rd cuts) and partly to the difficulties of extracting clover roots in the stony soils where wet sieving was not possible (because of numerous small flints passing through the sieve).

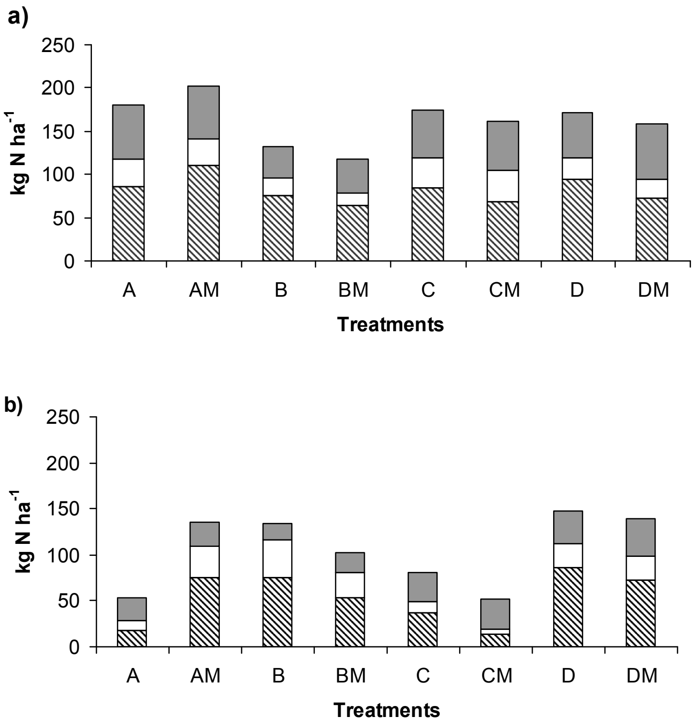


Figure 4 a) SW site and b) NE site. Organic N fractions in above-ground (>2.5 cm) herbage (shaded area), stubble and litter (open area) and macro organic matter (cross-hatched area) in the swards in autumn 2004. Treatments A: Red clover/grass sward (herbage cut and removed); B: Ryegrass only (herbage cut and removed); C: Red clover/grass sward (herbage cut and returned to plot); D:

Ryegrass only (herbage cut and removed, but mulched with herbage from A). Treatments A-D designated by M also received FYM. For between-treatment comparisons: ±SEM = 13 and 23 (SW and NE sites, respectively).

Annual yields of herbage dry matter (DM) for both sites in 2003 are shown in Figure 5. The inherent fertility of the soils at both locations could be assessed from the yields obtained in treatment B (ryegrass, cut and removed), which gave an indication of the abilities of the two soils to support plant growth without input of additional nutrients, viz. 5.9 and 6.9 t DM ha^{-1}, for the plots without FYM at the SW and NE sites, respectively. The addition of FYM did not improve the yields significantly at either site, except in the first cut ($P<0.05$, data not shown), but there was a consistent (but non-significant) trend at both sites for the FYM-treated swards to exceed the yields of swards that did not receive FYM. Mulching increased ($P<0.001$) the yield of the grass only swards at both sites (i.e. treatment D compared with B) and also in the clover treatments (i.e. treatment A compared with C), at the NE site only.

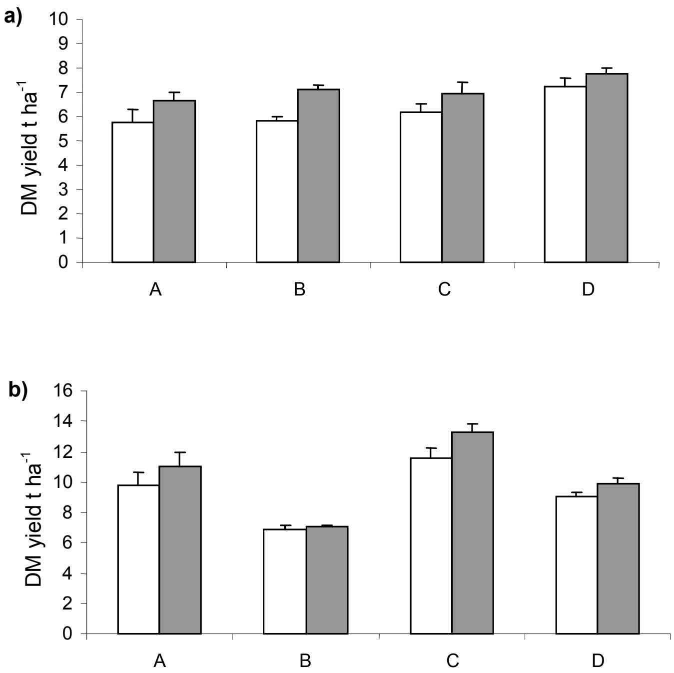
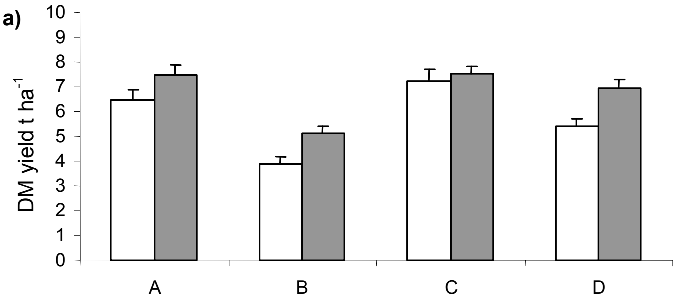


Figure 5 a) SW site and b) NE site. Total dry matter (DM) yields in 2003. Treatments A: Red clover/grass sward (herbage cut and removed); B: Ryegrass only (herbage cut and removed); C: Red clover/grass sward (herbage cut and returned to plot); D: Ryegrass only (herbage cut and removed, but mulched with herbage from A). Treatments A-D without FYM are shown as open histograms and those with FYM are shaded. Bar = +SEM.

The establishment of clover was slower at the SW site than at the NE site. Harvested herbage yields contained 74% clover content in SW compared with 94% in NE in 2003. The poorer establishment of red clover at the SW site may have been due to the exceptionally dry spring and summer months experienced in 2003, as well as competition from a high number of weeds that germinated from the seed bank. Although the weeds were largely controlled by the cutting regime, the effect was carried through to the second year.

In the 2004 harvest year, FYM increased yields ($P<0.01$) at both sites (Figure 6) in the cut swards without mulching (treatments A and B), but there was no effect of FYM when swards also received mulch (treatments C and D). At the NE site, the effect of mulching was more marked in the absence of manure but, even when manure was applied, the yield of mulched clover and grass (treatments C and D) was greater ($P=0.05$) than without mulching. At both sites, maximum yields were obtained in this second harvest year: 7.5 t ha^{-1} and 14.5 t ha^{-1} dry matter (in treatment C) at the SW and NE sites, respectively, reflecting the greater proportion of clover in the NE swards. Another reason for the SW site achieving only about half the yield of the NE site was that the soil at the former site tended to be prone to drought which would particularly affect the performance of clover and make it less competitive in a mixed sward.

a)



b)

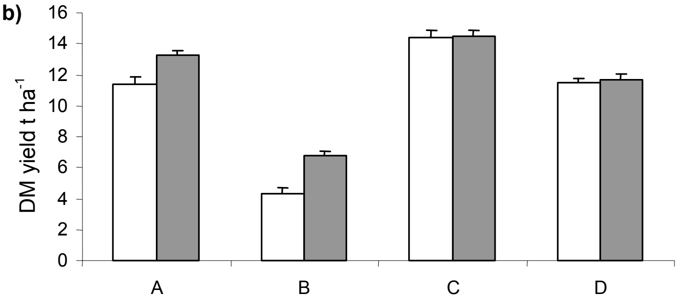


Figure 6 a) SW site and b) NE site. Total dry matter (DM) yields in 2004. Treatments A: Red clover/grass sward (herbage cut and removed); B: Ryegrass only (herbage cut and removed); C: Red clover/grass sward (herbage cut and returned to plot); D: Ryegrass only (herbage cut and removed, but mulched with herbage from A). Treatments A-D without FYM are shown as open histograms and those with FYM are shaded. Bar = +SEM.

Nitrogen yields as measured in total annual herbage N offtake in the harvested herbage in 2003 and 2004 are shown in Table 1 for both sites. Soil N supply (estimated from treatment B, grass/no mulch) was similar at both sites in 2003 (*c.*100 kg N ha^{-1}), but was reduced in both soil types by about 30% in 2004; this could also be seen in the low soil mineral N reserves recorded after two years' cropping (without mulching) at both sites.

Table 1. Nitrogen supply from soil, mulch and FYM and effects on N fixation (kg N ha^{-1}) as measured in total annual herbage offtake at the SW and NE sites. Treatments were: A, clover/grass cut and removed; B, grass cut and removed; C, clover/grass cut and mulched; D, grass cut and removed, then mulched with herbage from A.

Treatments	N Sources	SW site				NE site			
		2003		2004		2003		2004	
		-FYM	+FYM	-FYM	+FYM	-FYM	+FYM	-FYM	+FYM
	Measured								
A	N from soil + fixation	145^{ab}	173^{a}	197^{b}	226^{a}	282^{a}	303^{b}	282^{b}	317^{a}
B	N from soil	108^{c}	131^{c}	77^{d}	105^{c}	98^{b}	110^{d}	69^{d}	110^{c}
C	N from soil + fixation + mulch	158^{a}	173^{a}	226^{a}	234^{a}	327^{a}	375^{a}	354^{a}	342^{a}
D	N from soil + mulch	140^{b}	151^{b}	116^{c}	154^{b}	151^{b}	168^{c}	191^{c}	196^{b}
	Derived								
D-B	N from mulch	32	20	39	49	53	58	122	86
A-B	N fixed with no mulching	37	42	120	121	184	193	213	207
C-D	N fixed with mulching	18	22	110	80	175	206	162	146
(A-B)-(C-D)	Reduction in N fixation through mulching	19	20	10	41	9	-13	51	61

Values with different subscripts within columns are significantly different ($P<0.05$).

Using measured data from the four treatments, it was possible to derive separate estimates for the effect of mulch on N fixation. At the SW site in 2003, N fixation (no mulching) was <40 kg N ha^{-1}, but increased by three-fold in 2004, as the swards became better established (*c*. 50% clover). Whereas, with the higher clover content swards established at the NE site (*c*. 70% clover in 2004), fixation was about 200 kg N ha^{-1} in both harvest years. There was a reduction in N fixation in the presence of mulch in all treatments in both years (range 9 to 61 kg N ha^{-1}); the exception was the NE site in 2003 where in the presence of FYM mulching appeared to have slightly enhanced N fixation (P = 0.057) by 13 kg N ha^{-1}.

If 2003 is regarded as an establishment year, then by 2004 it is clear that, at both sites, the order of response in N yield between treatments was consistent and comparable, either with or without added manure. For example, at both sites, treatment C (with mulch) exceeded the other treatments in N yield (P< 0.05) where no FYM was added, but gave similar N yields to treatment A (no mulch) where FYM was added. This suggests an interaction between the added FYM and mulch which was sufficient to depress N fixation by an amount roughly equal to the amount of N gained from the amendments.

Release Phase

The mean content of mineral N in the upper soil profile (0-30 cm) immediately before ploughing in of the swards in spring 2005 was 49 kg N ha^{-1} at the SW site and 120 kg N ha^{-1} at the NE site. At both sites, there was more mineral N on the previously mulched plots, with means of 43 and 97 kg N ha^{-1} for treatments A and B compared with 54 and 142 kg N ha^{-1} for treatments C and D (SW and NE sites, respectively). The increase in mineral N compared with the previous autumn indicated that there had been mineralisation of N over the winter period. At the end of the release phase in autumn 2005, the overall means were 7 and 78 kg N ha^{-1} at the SW and NE sites, respectively, showing a rapid depletion of mineral N from the upper soil profile in the SW site with the onset of drainage in this free draining soil.

The effect of build-up treatment on ryegrass yield was clearly seen in the first cut at both sites, with significant differences between manure and legume management treatments (Figure 7). These differences were also seen at the NE site in the second cut.

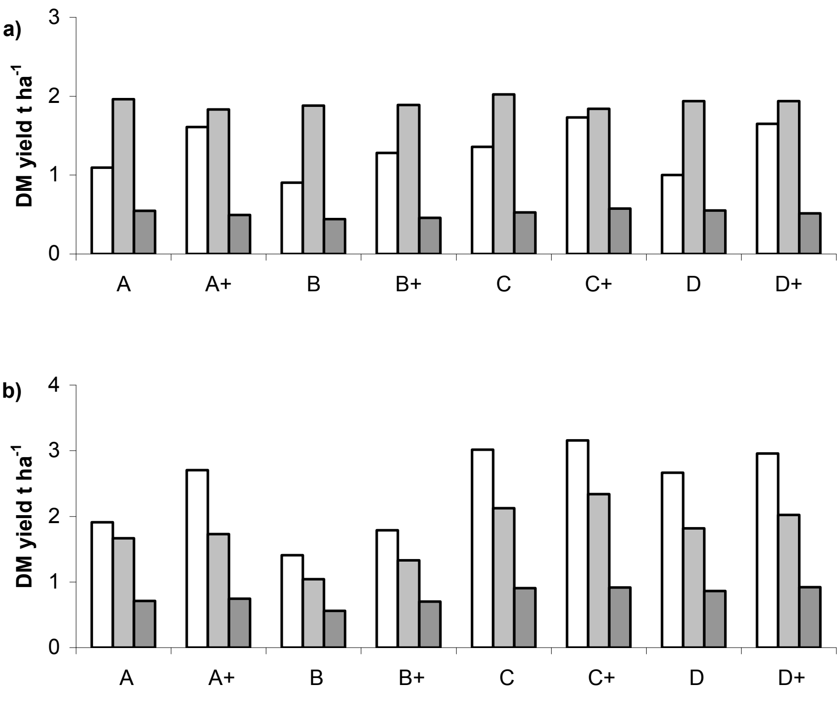


Figure 7. a) SW site and b) NE site. Total ryegrass biomass yields in 2005. Previous treatments (2003-4) were A: Red clover/grass sward (herbage cut and removed); B: Ryegrass only (herbage cut and removed); C: Red clover/grass sward (herbage cut and returned to plot); D: Ryegrass only

(herbage cut and removed, but mulched with herbage from A). Treatments A-D with '+' represent 'with FYM'. 1st cut, no shading; 2nd cut, light shading; 3rd cut, dark shading.

The amount of N released following ploughing-in was assessed as N yield by measuring the uptake of nitrogen in the harvested ryegrass crop during the 2005 growing season (Table 2). Irrespective of management history, N yield was higher at the first cut where there had been a history of FYM applications but the impact of previous manure had dissipated by the second (24 (SW) and 25 (NE) weeks after destruction) and third (30 (SW) and 31 (NE) weeks after destruction) cuts. At first cut N offtake was larger in clover/grass plots compared with the corresponding grass only plots (A/B and C/D). N offtake was larger in the mulched plots compared with the corresponding unmulched plots (A/C and B/D). These differences were significant at the p=0.05 level at the NE site and (except for A/C which was non significant and A/B which was significant at p=0.05) at the p=0.10 level at the SW site. At the NE site these differences remained significant at the second cut and there was still a benefit from mulching at the third cut. At the SW site there was a larger N offtake from the grass only plots (B and D) at the second cut than at the first suggesting that mineralisation of the grass residues may have been slower than those of the grass/clover.

Table 2. Nitrogen released in 2005 following sward destruction as measured by N offtake (kg ha^{-1}) in the following crop at the SW and NE sites. Previous treatments (2003-4) were: A, clover/grass cut and removed; B, grass cut and removed; C, clover/grass cut and mulched; D, grass cut and removed, then mulched with herbage from A.

		1st cut				2nd cut				3rd cut			
		IGER		HM		IGER		HM		IGER		HM	
	Build-up treatment	+FYM	-FYM	+FYM	-FYM	+FYM	-FYM	+FYM	-FYM	+FYM	-FYM	+FYM	-FYM
	Measured												
A	soil+clover	56	44	62	44	51	55	24	24	14	18	15	15
B	Soil	44	33	38	30	49	49	20	17	13	12	15	12
C	soil+clover+mulch	65	48	77	72	51	56	38	33	17	15	19	19
D	soil+mulch	58	36	66	63	53	51	33	29	16	15	19	18
	Derived												
D-B	N from mulch	14	3	28	33	4	2	13	12	3	3	4	6
A-B	N from clover without mulching	12	11	24	14	2	6	4	7	1	6	0	3
C-D	N from clover with mulching	7	12	11	9	-2	5	5	4	1	0	0	1

There was positive linear relationship between N capture (as measured by N offtake) and total N supply (as measured by SMN and N in crop residues) but the impact of the individual N supply components on this relationship varied between sites and between cuts. At the SW site the soil mineral component was most important of all the parameters at 1st cut and there was no relationship at later cuts. At the NE site the above-ground crop N component was the most important parameter with root N and SMN 0-30 cm depth of lesser but similar importance for 1st cut, whilst at the 2nd cut the SMN 0-30 cm depth became more important than the root N.

4.3.2. Demonstration plots

Following consultation with the industry, observation plots were set up in spring 2003 at ADAS High Mowthorpe and Duchy College Cornwall with additional industry funding. A third site at Unilever Bedford was abandoned due to weed and rabbit problems. Novel legume crops were established to observe how they performed under UK conditions. The crops were: subterranean clover (*Trifolium subteranneum*); Persian clover (*Trifolium resupinatum*); Egyptian clover (*Trifolium alexandrinum*); large birdsfoot trefoil (*Lotus pedunculatus (L. uliginosus)*); trefoil, black medick (*Medicago lupulina*); white-flowering lupin (*Lupinus alba*); yellow-flowering lupin (*Lupinus luteus*); narrow-leafed/blue lupin (*Lupinus angustifolius*); soya beans (*Glycine max*); lentil (*Lens culinaris*); galega, goat's rue (*Galega orientalis*); white sweet clover (*Melilotus alba*); chickpea (*Cicer arietinum*); fenugreek (*Trigonella foenum graecum*). White clover (*Trifolium repens*), red clover (*Trifolium pratense*) and ryegrass (*Lolium perenne*) were grown for comparison. Two crops, galega and soya, were failures at both sites whilst chickpea also failed at Duchy College. Each forage species was cut twice, whilst grain species taken to harvest. The plots were then ploughed-in and sown to ryegrass. N fixation was assessed by measuring N uptake in the ryegrass in the following year.

The novel crops generated much farmer interest, notably sweet white clover, which made a great deal of growth in only a few weeks although it did not respond well to cutting. Some of the grain legumes such as lentils ripened unevenly suggesting that if they are to be grown commercially, techniques such a 'swathing' (as used for oilseed rape) may be needed.

Based on N yield (as measured in N offtake in the following ryegrass crop) sweet white clover, large birdsfoot trefoil and subterranean clover appeared to have fixed a similar amount of N compared with white or red clover at High Mowthorpe. At the Duchy College, where the soil N supply was large (due to rotational position), none of the legumes out performed the ryegrass. More work is needed on the agronomy of these crops to establish the best management practices for them and to compare their effectiveness as N fixers with more commonly used species.

4.3.3. On-farm monitoring (Objective 6)

Plots were set up at several commercial farms to follow the fate of N after ploughing fertility-building crops. The site details are shown in Table 3.

Table 3. Cropping sequences at each of the 12 farm monitoring sites.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Autumn 02	Red Clover grazed by sheep/cattle	Clover cut for silage	Clover cut for silage	Clover cut for silage slurry used	Vetch	Grass/clover ley grazed by cattle
Winter 02/03	Red Clover grazed by sheep/cattle	Triticale	Triticale	Triticale	Vetch	Grass/clover ley grazed by cattle
Spring 03	Barley sown 31/3/2003	Triticale	Triticale	Triticale	Vetch	Grass/clover ley grazed by cattle
Summer 03	Estimated Barley yield 1.5tons /acre.	Triticale harvested, mustard planted as cover crop	Triticale harvested, mustard planted as cover crop	Triticale harvested estimated yield 2t/acre+1.5t/acre straw	Vetch ploughed in with 25t/acre FYM then cauliflowers planted	FYM ploughed in June for cauliflowers, rabbit damage then stubble turnips
Autumn 03	Rape and turnips.	Mustard	Mustard	Slurry applied then white clover	Cauliflowers	Stubble turnips
Winter 03/04	Strip grazed over winter by cattle	Mustard	Mustard	White clover	Cauliflowers harvested Jan-Mar	Stubble turnips
Spring 04	April going into peas and barley	Mustard, then barley u/s clover	Mustard, then barley u/s clover	White clover cut for silage	Lupins planted	Stubble turnips ploughed in
Summer 04	50:50 peas/barley	Barley with a few peas undersown with white clover	Barley with a few peas undersown with red clover	White clover cut for silage	Lupins	White clover ryegrass mix. To be grazed

	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12
Autumn 02	Grass/clover (grazed by cattle)	Winter wheat, undersown with trefoil	Grass/Clover (2 years)	Grass/Clover (2 years)	Clover (1 year)	Clover (1 year)
Winter 02/03	Winter wheat		Triticale	Winter wheat		
Spring 03	Winter wheat	Spring Beans	Triticale	Winter wheat	Potatoes	Spring wheat
Summer 03	Winter wheat (5.45 t/ha)	Spring Beans (3.66 t/ha)	Triticale (3.59 t/ha)	Winter wheat (3.75 t/ha)	Potatoes (35.09 t/ha)	Spring wheat (3.27 t/ha)
Autumn 03			Winter wheat	Phacelia	Winter wheat	Spring wheat
Winter 03/04			Winter wheat	Phacelia	Winter wheat	Spring wheat
Spring 04	Spring barley		Winter wheat	Spring barley	Winter wheat	Spring wheat
Summer 04	Spring barley		Winter wheat	Spring barley	Winter wheat	Spring wheat

Shading indicates a fertility-building crop.

Soil was sampled prior to ploughing-in to estimate the available N resulting from the fertility building crops. Cores were also taken of above-ground crops and below-ground roots and fractionation data showed that the distribution of N between above-ground and below-ground components could vary a great deal (150-450 kg ha^{-1} N), but the amount in the roots was consistently large (Figure 8).

The quantity of the N that is readily available for the following crop depends, to some extent, on the C:N ratio of each component of the organic matter: the narrower (smaller) the C:N ratio, the more likely it is that the organic matter will easily degrade to release N to plant available forms. The plant fractions obtained from the 12 farm sites all had a C:N ratio of less than 25:1 and would, therefore, be expected to produce slow mineralisation and a steady release of mineral N for the following crop(s). The clover herbage had the smallest C:N ratio (mean: 14:1) and the litter/stubble fraction (contains clover stolons, as well as a mixture of decaying leaf and stubble materials) had the largest C:N ratio (mean: 22:1). These data were used in the model development work.

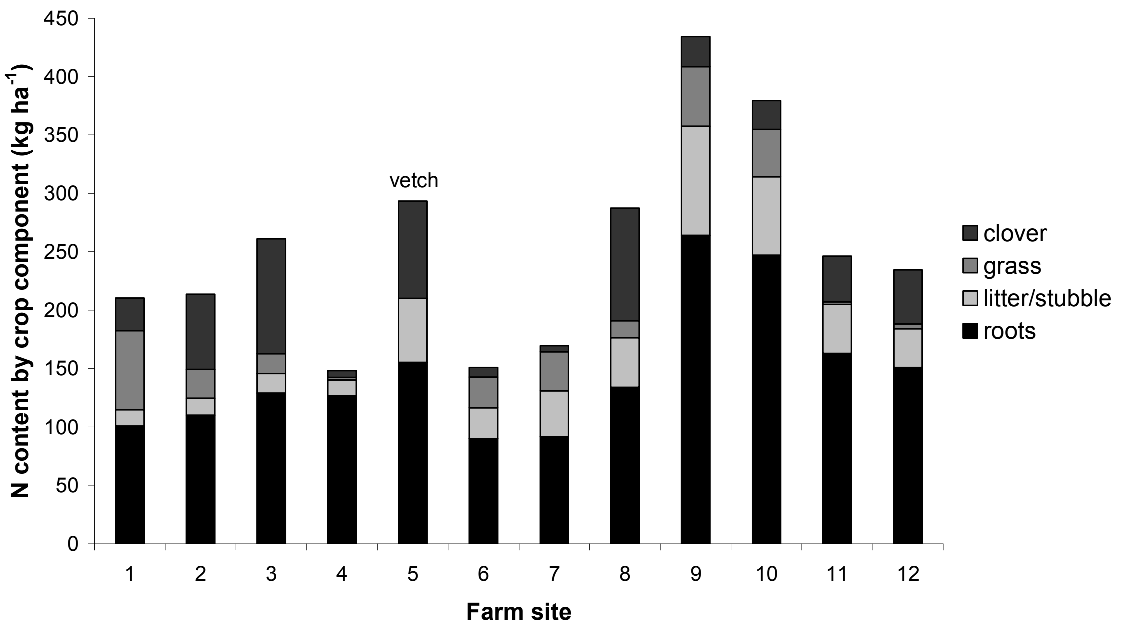


Figure 8. N content by crop component for each on-farm monitoring site.

4.4. Model Development (Objective 5)

The FBC model was produced to assist organic growers and advisors in designing crop rotations and making efficient use of the N that is available - in particular, to provide information about whether the fertility-building phase will provide sufficient N to sustain the cropping phase of the planned rotation and to indicate where N savings might be achieved by reducing N losses. The model provides an estimate of the likely crop yields achievable with the particular level of N supply and also estimates the scale of N losses. It was designed to only require the sorts of input data that would be available to a commercial grower.

The model is currently written in the form of an Excel spreadsheet. To make it more user-friendly and suitable for demonstrating at farmers' meetings, all versions of the model have included a simple input page with drop-down menus, etc. Output is provided as simple graphs and tables linked to the input page. The objective was to include a satisfactorily wide range of crops and growing conditions within the model to allow the majority of users to exactly describe their particular rotation, without having to select the 'most-similar' option, which can often produce misleading results.

The model operates at a field-scale with a monthly time-step. Simulation of the arable cropping phase of the rotation is based on the ADAS Stix model (Defra project NT2501), though it has been considerably modified and extended for the present purpose. This provides an estimate of N mineralisation from the soil and from crop residues, together with estimates of crop growth, N uptake and N leaching. An important change for the FBC model is that the main part of the N mineralisation from the fertility-building phase and crop residues is described as a first-order reaction, rather than the zero-order, broken-stick approach used in the Stix model. An extra section has been added at the start of the FBC model to provide an estimate of the N present in the soil and in sward residues at the end of the ley phase of the rotation. This sets the starting conditions for the subsequent estimates of N mineralisation and N supply during the arable cropping phase.

In its current form, the input screen (Figure 9) requires the user to enter the UK region for the farm and dominant soil type for the field. Climatic conditions are set within the model, based on the monthly average conditions for the selected region, except that annual rainfall for the site can be entered separately, if desired. The next section requests the following information about the fertility-building phase ley phase; type of ley (white clover, red clover, lucerne, white clover/grass or red clover/grass), management of the ley (cut, grazed, mulched), number of cuts per year, number of years in the ley, legume content of the sward (low, medium, high), whether manure has been applied to the ley, and previous cropping (long-term arable, long-term grassland, ley-arable) and date of incorporation of the ley.

The final section of the input screen allows the entry of information about the arable cropping phase. The model allows for up to five cropping years after the fertility-building phase, with either one or two crops per year. For each crop, the user selects the crop name, sowing date, harvest date, expected yield (optional), proportion of weeds in the crop and whether or not the straw/crop residue is removed at harvest. Current crop options include 24 agricultural and horticultural crops, a cover crop, uncultivated fallow and weeds. The input screen also allows the user to enter up to two manure applications per year (manure type, application rate, application date and time to incorporation).

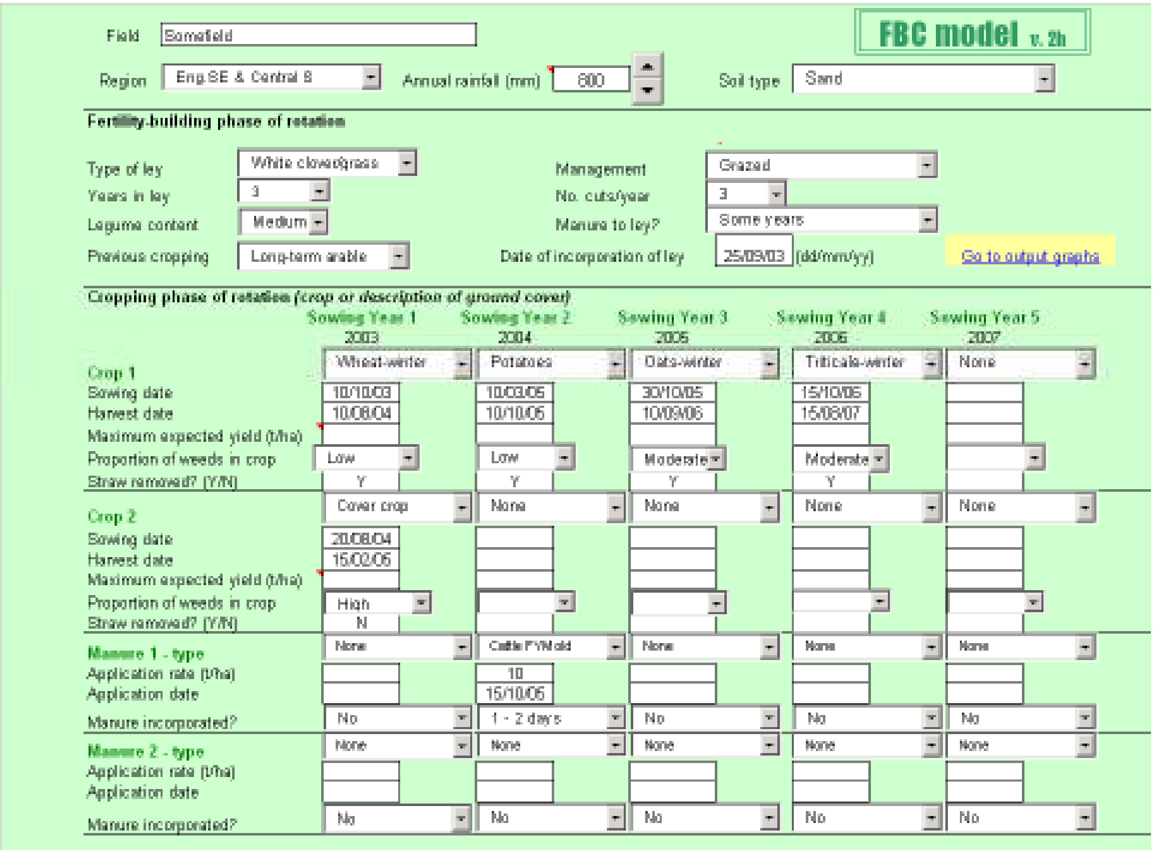
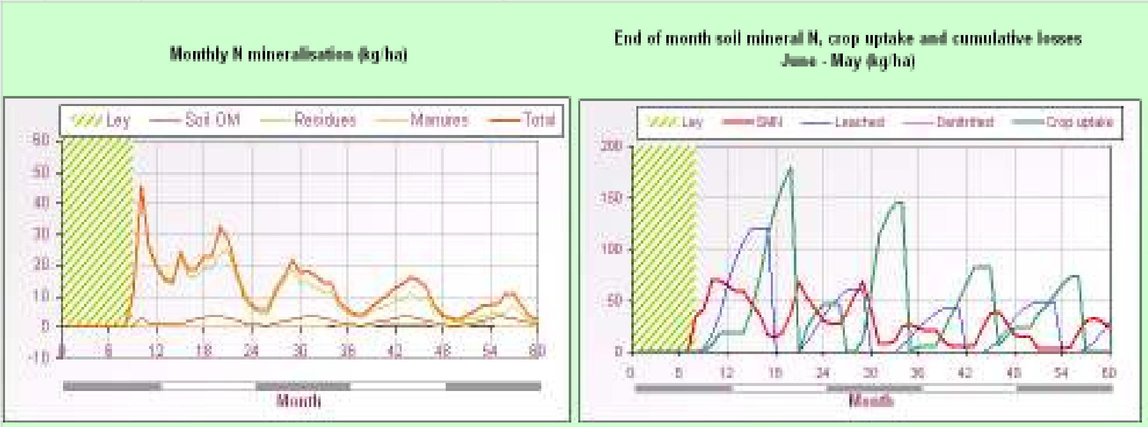


Figure 9. Input screen for the FBC model.

Output from the model is presented as two graphs (Figure 10), showing (a) the monthly pattern of N mineralisation from soil organic matter, crop/ley residues and manures and (b) cumulative crop N uptake, monthly soil mineral N status, N leaching and denitrification. There is also a table comparing the N uptake required to produce the maximum or target yield for each crop and the actual N uptake achieved. The table also shows the crop yield achieved and winter N losses by leaching and denitrification.

The FBC model starts with an estimate of the total amount of N in the fertility-building ley residues when first incorporated and the C:N ratio of these residues. Values for the different types of ley and different ley managements were determined by a separate model, based on information in Whitehead *et al.*, [16]. These values are included as a look-up table within the FBC model. This provides the starting conditions for the more-detailed calculations of the monthly N mineralisation steps, which start from the date of incorporation of the ley. For each month, the model calculates the amount of mineral N released from the ley residue and from soil organic matter and from any manure applications (Figure 11). To this is added the input of N in rainfall and immediately available mineral-N from any manure applied that month (after correcting for N lost by ammonia volatilisation). This determines the amount of mineral N in the soil profile that month. In later months, after the growth and harvest of one or more crops, the profile receives additional inputs from the mineralisation of N from these later crop residues.



(a) Crop N required for max. or target yield compared with crop N achieved

	Crop	N for max or target yield (kg/ha) crop limit	climate limit	N in crop (kg/ha)
Year 1	Wheat-winter	210	185	162
	Cover crop	77	73	46
Year 2	Potatoes	251	189	146
	None	---	---	---
Year 3	Oats-winter	158	158	70
	None	---	---	---
Year 4	Triticale-winter	168	168	63
	None	---	---	---
Year 5	None	---	---	---
	None	---	---	---

(b) Harvested yield

FWt yield (t/ha)
6.5
0.0
34.8

2.7

2.1

(c) N losses (November to March)

	Leached (kg/ha)	Denitrified (kg/ha)
Year 1	104	0
Year 2	50	0
Year 3	36	0
Year 4	38	0
Year 5	---	---

Return to Input

Model development funded by Defra

Figure 10. Output screen for the FBC model.

A simple crop growth model uses the average monthly solar radiation, temperature and soil moisture for the region to calculate crop growth for that month under conditions of non-limiting N supply, and the crop N requirement corresponding to this yield. At this stage, growth is allowed to continue up to the maximum yield set for the crop, or up to the date of senescence or harvest of the crop. This monthly crop demand is compared with the quantity of N in the soil profile down to the maximum rooting depth the crop has achieved in that month. If there is sufficient N available in the soil, the crop is allowed to grow at the calculated rate and satisfies the N demand by removing this quantity of N from the soil. If the N available in the profile is less than the crop demand, N uptake is limited by the available N supply and growth is reduced accordingly. If weeds are present, they compete with the crop for the available soil N.

Where the soil N supply exceeds the crop demand, any surplus N in the profile is assumed to be available for loss by leaching or denitrification. Leaching is determined by calculating the hydrologically effective rainfall and allowing this to transport a proportion of the available N from one 5-cm soil layer to the next, sequentially down the profile. Nitrogen leaving the base of the profile (at 100 cm depth or 40 cm for shallow soils) is assumed to have been leached. Denitrification cannot be satisfactorily estimated with a simple model operating at a monthly time-step. However, denitrification can be an important form of N loss under some conditions and it is important that growers should be made aware of potential losses by this process. The model, therefore, provides an estimate of denitrification, based on the concentration of mineral N in the soil, temperature and whether or not the soil profile is saturated, accepting that this simple estimate will have a high degree of uncertainty. Mineral N in each 5-cm layer of the soil profile that has not been taken up by the crop or lost is carried forward to the next month.

At harvest, the final crop yield is the maximum yield achievable for that particular level of N supply. If N is not limiting, the yield is determined by the climatic conditions or maximum yield limit set for the crop. Nitrogen in the harvested crop, together with N in any harvested straw, is removed from the field and is not included in any of the subsequent calculations. Nitrogen in stubble and roots and in straw or crop residues not removed from the field is returned to the soil as an additional residue pool, from which the N release is modelled (based on the amount of N and the C:N ratio of the residues). Where weeds are present, they are included in the straw and stubble/root pools.

The model allows for the inclusion of leguminous crops during the arable phase of the rotation (peas, beans, vetch) by allowing for part of the crop's N requirement to be supplied by N fixation and reducing the crop N demand from the soil by an equivalent amount. This remaining N is taken up from the soil in the same way as for non-leguminous crops. The proportion of the total crop N demand supplied by N fixation is set for each crop type and modified by a variable reduction factor, so that the N derived from fixation falls with increasing concentration of mineral N in the soil [13].

The emphasis during this stage of model development was to produce a modelling framework that could handle the wide range of crops and managements found in organic farming rotations. In the time available, it was not possible to fully refine all the crop and soil parameters used in the model, particularly for those crops for which there is little published information in the literature. The current version of the model appears to provide a satisfactory qualitative description of N availability and losses under the conditions for which it has been tested. However, it is recognised that many of the crop and soil parameters currently used in the model could be improved and this would improve the quantitative predictions from the model. It demonstrates the potential for a relatively simple model using readily-available input data to provide a planning tool for improving the efficiency of N use in organic farming rotations.

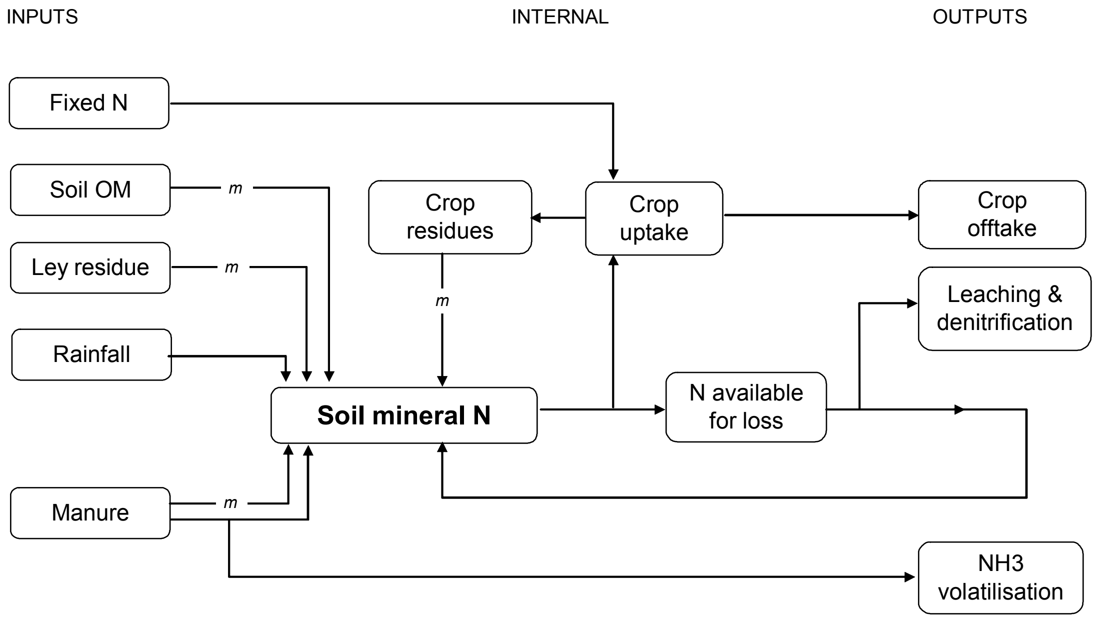


Figure 11. Flow diagram for N in the FBC model (m denotes the mineralisation processes determined in the model).

The original project objectives recognised that, in the time available, it would not be possible to produce a fully-validated model suitable for general release. Instead, the model would be used to prepare a series of look-up tables to be included in the Guidelines booklet (Objective 7).

4.5. Guidelines booklet (Objective 7)

The final deliverable of the project was planned as a Guidelines booklet that aimed to summarise the main conclusions from the project, presented as practical advice for the farming community. This was to include estimates of N supply from fertility building crops. The project has already described the many factors that affect N supply and the complexity of their interactions: hence the need to develop the FBC model to quantify effects. However, the booklet required a simplified method of providing estimates of N supply. To achieve this, a simple flow diagram calculator was developed (Figure 12). The booklet includes a number of look-up tables and, using this simple flow diagram, guides the user through the calculation steps necessary to estimate:

- The amount of N accumulated during the ley phase of the rotation
- The N available to following crops and the likely yields under this level of N supply

This form of presentation has to adopt a much-simplified approach and a very restricted range of cropping options, both of which severely limit the value of this method of presentation and demonstrate the need for more adaptable and widely applicable computer-based models.

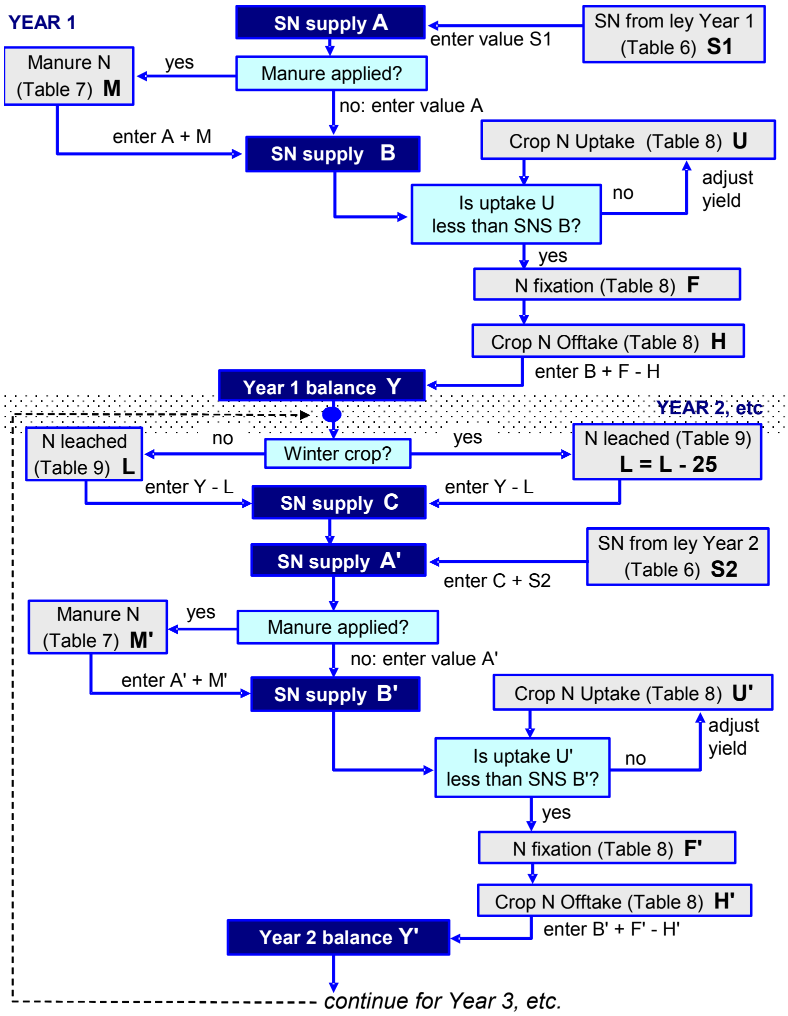


Figure 12. Flow diagram showing the stages in calculating the N available to crops in the first and second years after cultivating the ley.

Farmer feedback on both the FBC model and the simple flow diagram calculator were sought at workshops at the end of the project. These comments were incorporated and the final version of the latter is included in the Guidelines booklet (appended in Annex 3).

5. CONCLUSIONS

The literature review served as a good starting point for the project and the project team were able to capitalise on existing research data. This was important, given the complexity of the subject and the need to avoid repetition. The conclusions that we were able to draw from the large body of work were able to serve three purposes:

- Form the basis of advisory literature
- Inform our research programme
- Inform the FBC model development

The full review is appended as Annex 1, the main conclusions were:

- The amount of N fixed by different legumes is determined by the inherent capacity of the crop/rhizobium symbiosis to fix N, modified by the crop's growing conditions (e.g. soil, climate, disease), crop management and length of time for which the crop is grown. Consequently, the influence of all of these factors means that a wide range of values have been reported by different researchers. However, for a particular legume species there is usually a close relationship between yield and the quantity of N fixed. Figure 2 indicates the range of fixation estimates quoted for a number of leguminous crops and was generated from the literature review.

- The literature provides considerable evidence that management factors can influence N fixation by a legume. The presence of soil mineral N is generally thought to reduce fixation capacity. It was hypothesised that factors that would increase the soil mineral N pool (manure application, cutting and mulching, grazing) would decrease N fixation (this was tested in the field experiments. Fixation tends to decrease with legume age, mainly because the amount of soil N tends to increase. Consequently, there are many of these contradictions, which make management decisions difficult. For example, cutting and mulching is a standard practice in organic rotations, especially in stockless systems, yet it may be that such a practice is decreasing fixation and the amount of N imported into the rotation from the atmosphere.

- Harvesting of forage or grain will remove much of the fixed N and reduce the benefit to following crops (see Figure 2). The benefit will be further reduced if straw and other crop residues are also removed from the field. However, much of the fixed N will be retained within the farm if the forage and grain is fed to stock on the farm rather than being sold. Other aspects of management affecting N-fixation include position of the crop in the cropping rotation, duration of cropping and methods of cultivation. These are detailed later. Growing the legume in a mixture with a non-fixing crop can increase the proportion of N obtained from the atmosphere. For example, in grass/clover leys, the grass utilises soil-N and thus avoids the build-up of N that otherwise might inhibit fixation. However, the presence of a companion crop also reduces the number of N-fixing plants per unit area.

- Before N from the legumes can be used by the next crop, it has to be 'mineralised' into plant available forms (nitrate and ammonium). Some will already be in this form, due to transformations during the life of the crop. Most, however, will need to be mineralised by microbial action after cultivation. Since mineralisation is a microbial process, the rate depends on environmental conditions (soil moisture, temperature, etc), soil texture (potentially slower in clays than sands) and also the composition of the crop material (fresh green residues decompose more rapidly than old 'stemmy' materials). The dynamics are therefore complex and we used computer models to develop guidelines on the rates of breakdown.

- Once mineralised, N is also susceptible to loss and it is important that as much as possible is retained for use by the crop. Losses occur mainly through nitrate leaching and, sometimes, ammonia volatilisation. Nitrate leaching can be minimised by ploughing the ley as late as possible in the autumn or preferably in the spring. However, this advice does not always fit with more practical considerations of preparing the soil for the next crop. Nitrate leaching after ploughing the ley probably represents the greatest N loss from the rotation. Ammonia volatilisation can occur from the cut foliage, but amounts are thought to be small. The main loss of ammonia is from manure (during grazing or after application). Whereas grazing losses are difficult to control, rapid incorporation of manure after application will reduce volatilisation losses.

Although the project was science-based, **industry involvement** was critical to ensure that the end results of the project were of value and useful; hence our emphasis on stakeholder engagement at start, middle and end of the project. The industry has been supportive throughout.

The **field experiments** focused on specific issues. With industry guidance we chose to investigate in detail the effects of fertility-building crop management on N fixation. Our hypothesis that factors which increase soil mineral N supply reduce fixation, was developed from the literature review.

The field experiment data showed that in terms of N fixation maximum N yield (as measured by N offtake) occurred in the mulched grass/clover sward. But, using the measured data, separate estimates for the effect of mulching on N fixation showed a reduction of between 9 and 61 kg ha^{-1} N. In the presence of FYM there appears to have been an interaction with mulching which was sufficient to depress N fixation by an amount roughly equal to the amount of N gained from the manure. Availability of fixed N for growth of the following crops is also important.

The amount of N released following destruction of the experimental swards was assessed by measuring the uptake of nitrogen in the following ryegrass crop. Irrespective of management history, N offtake was higher at the first cut where there had been a history of FYM applications. There was positive relationship between N capture (as measured by N offtake) and total N supply (as measured by SMN and N in crop residues) but the impact of the individual N supply components on this relationship varied between sites and between cuts.

Recommendations to organic farmers from this part of the work, are therefore to cut and remove herbage during the fertility building phase. This may be difficult for non-livestock enterprises and care needs to be taken that the mulch does not kill-out the receiving crop. Application of organic manures to legumes should also be avoided if the maximum amount of atmospheric N is to be fixed.

The project also produced some novel data on fractionation, which quantified the plant and soil N status after the fertility building stage in a range of commercial fields, highlighting the high proportion of nitrogen held within the root component of the fertility building crops.

Model development was a key part of the project and whilst it was never the intention to develop a fully functioning DSS within the project resource it was necessary to develop and use a spreadsheet model to formalise the thought processes. This capitalised on existing modelling approaches (NT2501) and was used to generate results for the guidelines booklet. Both the FBC model and the simpler Flow Diagram were well received by the industry during the various events which formed part of the **knowledge transfer** component of the project.

6. IMPLICATIONS OF THE FINDINGS

The outputs help Defra meet its policy objectives, in supporting organic farming and in facilitating better N utilisation within the rotation, thereby helping to minimise losses of N to the wider environment.

The project outputs give practical advice to organic farmers and growers. The results provide a better understanding of nitrogen accumulation under fertility building crops and its subsequent release. This is important in terms of rotation planning where it can help to maximise the yield potential of high value crops, and hence improve overall biological and economic sustainability. Confirmation that high soil nitrogen (either from application of FYM or mulch) reduces fixation is a significant finding.

With further development, the FBC model has the potential to be used as a fully operational Decision Support System, either as a stand-alone package, or via a website.

The information on fixation, soil N build-up and subsequent release under different legumes is also of value to non-organic farmers. They face escalating input costs and environmental restrictions, and are looking for ways of reducing reliance on purchased synthetic fertilisers.

The results may be of use in improving the soil nitrogen supply estimates in Defra's fertiliser recommendations reference book (RB209).

7. RECOMMENDATIONS FOR FUTURE WORK

Feedback from farmers, and the results from the novel-legume demonstration indicate that more work is needed on the less well-understood legume species. This work might be appropriate for LINK funding. There is also a potential connection with climate change issues as some legumes are better able to withstand drought than others.

Given the suppressing effect of FYM, which has a low available N content, on N fixation, there is also a need to understand the extent to which manures with more readily available N (e.g. cattle slurry and poultry manure) can adversely affect N fixation.

The fractionation data from the on-farm monitoring indicated that there is variation in the amount of both carbon and nitrogen being ploughed-in following fertility building crops. The C:N ratio is known to affect the rate of breakdown and the potential for carbon sequestration in organic farming is worth investigation.

The model currently concentrates on losses of N via leaching. Data is needed on the potential of gaseous losses, and how this is affected by management practices such as mulching.

There are opportunities to extend the model to cover a wider range of cropping situations. Also, some farmers expressed interest in using the FBC model for themselves. This would need further work to make it more suitable as a DSS for farmers, either as a stand-alone package or via the website.

There was considerable interest and enthusiasm for the FBC model at the farmers' meetings and a clearly expressed desire to have it made available to the industry. This would require a revision of those crop and soil parameters for which temporary, approximate values have been used in the current version and a more detailed validation of the model than has been possible in the present project. Also, a number of sub-routines are not fully implemented in the current version of the model and would require further work. For example, the estimates of soil and residue N at the end of the ley phase are not fully linked to the site location code and as a result, do not reflect the variation in N accumulation in different regions.

Intellectual Property Issues

The endpoint of the original project was to produce the underlying principles to enable development of a model/DSS to allow farmers to quantify N supply from legumes. It was not intended to fully develop the software for such a DSS within this project; however, having achieved these objectives, a logical follow-on would be to develop such a software model, which may have IP implications.

8. KNOWLEDGE TRANSFER ACTIVITIES

8.1. Workshops/site meetings

A total of 6 farmer workshops were held during the first year of the project (2002), numbers attending varied between 10-20 people per workshop.

Two on-farm meetings (ADAS High Mowthorpe, and Duchy College) were held during summer 2003 at which visitors were able to see the experimental plots.

In March 2005, two meetings were held (East and South West) at which selected farmers were invited to review progress on the model and comment on the proposals for the Guidelines booklet.

To conclude the project, two meetings were held (Midlands (HDRA), and South West (Okehampton)) to report on the project findings and promote the Guidelines booklet. There was an exceptional turn out for the second of these events in Okehampton, with over 70 farmers attending the meeting.

8.2. Other Events

Project descriptions and results of the study have also been presented at:

May 2003: Duchy College Research Day, Stoke Climsland.
May 2004: Duchy College Research Day, Rosewarne.
February 2005: Riverford Organic Growers Group, Totnes.
April 2005: OCDP workshop at Rushwell, Wilts.
April 2005: OCDP workshop at Driffield, Yorks.
April 2005: OCDP workshop at Barton, Cambs.
July 2004: Penscawn Farm, Mitchell. Overview of project and results of fertility building trial as part of Organic Studies Centre: Protein Crops for Organic Livestock. (S.Roderick)

August 2004: Organic Farmer Day at IGER, North Wyke, Devon. Open day which included an overview of the project and a chance to view the experimental plots. With D.Hatch, S.Cuttle, G.Goodlass and S.Roderick.

8.3. Website

For the duration of the project results and information have been posted on the project website: www.organicsoilfertility.co.uk (see Figure 3). The website had its own email feedback system which has generated a number of enquiries from Europe and the USA as well as the UK.

9. REFERENCES CITED IN THIS REPORT

1. Wood, M. (1996). Nitrogen fixation: how much and at what cost? In: D. Younie (ed.) Legumes in Sustainable Farming Systems. Occasional Symposium No. 30, British Grassland Society, Reading. pp. 26-35.
2. Spiertz, J.H.J. & Sibma, L. (1986). Dry matter production and nitrogen utilization in cropping systems with grass, lucerne and maize. 2. Nitrogen yields and utilization. *Netherlands Journal of Agricultural Science* **34:** 37-47.
3. Paul, E.A. & Clark, F.E. (1996). Soil Microbiology and Biochemistry. 2nd Edition. San Diego, Academic Press.
4. Jensen, E.S. (1989). The role of pea cultivation in the nitrogen economy of soils and succeeeding crops. In: P. Plancquaert & R. Haggar (eds). Legumes in farming systems. Kluwer Academic Publishers, Dordrecht, Netherlands. pp. 3-15.
5. Fisher, N.M. (1996). The potential of grain and forage legumes in mixed farming systems. In: D. Younie (ed.) Legumes in Sustainable Farming Systems. Occasional Symposium No. 30, British Grassland Society, Reading. pp. 290-299.
6. Shepherd, M.A., Harrison, R., Cuttle, S., Johnson, D.B. & Gosling, P. (2000). Understanding Soil Fertility in Organically Managed Soils. MAFF Commissioned Review. Available for downloading at: www.adas.co.uk/soilfertility
7. Hartwig, U.A. & Soussana, J.F. (2001). Ecophysiology of symbiotic N_2 fixation in grassland legumes. In: Organic Grassland Farming (Eds J Isselstein et al.), Grassland Science in Europe, volume 6, pp. 1-10.
8. Streeter, J.G. (1988). Inhibition of legume nodule formation and N_2 fixation by nitrate. CRC Critical *Reviews in Plant Sciences* **7:** 1-23.
9. Hartwig, U.A. (1988). The regulation of symbiotic N_2 fixation: a conceptual model of N feedback from the ecosystem to the gene expression level. Perspectives in Plant Ecology, Evolution and Systematics 1, pp. 92-120.
10. Thornley, J.H.M., Bergelson, J. & Parsons, A.J. (1995). Complex dynamics in a carbon-nitrogen mosel of a grass-legume pasture. *Annals of Botany* **75:** 79-94.
11. Vitousek, P.M. & Field, C.B. (1999).Ecosystem constraints to symbiotic nitrogen fixers: a simple model and its implications. *Biogeochemistry* **46:** 179–202.
12. Wu, L & McGechan, M.B. (1999). Simulation of nitrogen uptake, fixation and leaching in a grass/white clover mixture. *Grass and Forage Science* **54:** 30-41.
13. Korsaeth, A. & Eltun, R. (2000). Nitrogen mass balances in conventional, integrated and ecological cropping systems and the relationship between balance calculations and nitrogen runoff in an 8-year field experiment in Norway. *Agriculture Ecosystems & Environment* **79:** 199-214.

14. Kristensen, E.S., Høgh-Jensen & Kristensen, I.S. (1995). A simple model for estimation of atmospherically-derived nitrogen in grass-clover systems. *Biological Agriculture and Horticulture* **12:** 263-276.
15. Carberry, P.S., McCown, R.L., Muchow, R.C., Dimes, J.P., Probert, M.E., Poulton, P.L. & Dalgliesh, N.P. (1996). Simulation of a legume ley farming system in northern Australia using the Agricultural Production Systems Simulator. *Australian Journal of Experimental Agriculture* **36:** 1037-48.
16. Whitehead, D.C., Bristow, A.W. & Lockyer, D.R. (1990). Organic matter and nitrogen in the unharvested fractions of grass swards in relation to the potential for nitrate leaching after ploughing. *Plant and Soil* **123:** 39-49.

ANNEXES SUBMITTED SEPARATELY AS PDF FILES

Annex 1. Literature Review

Annex 2. Advisory Leaflet

Annex 3. Guidelines Booklet

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Given the high importance placed on knowledge transfer within this project the results have been widely published in both the scientific and popular press.

Scientific Papers

D. J. Hatch, G. Goodlass, A. Joynes & M. A. Shepherd (2006). The effect of cutting, mulching and applications of farmyard manure on nitrogen fixation in a red clover/grass sward. Accepted for publication in *Bioresource Technology*.

G. Goodlass & D. J. Hatch (2006). The effect of cutting, mulching and applications of farmyard manure on release of nitrogen following destruction of red clover/grass sward. *In preparation*

Conference papers

S P Cuttle & G Goodlass (2004). Estimating nitrogen fixation by fertility-building crops. BGS/COR meeting 2004. Organic farming: science and practice for profitable livestock and cropping. Occasional Symposium, British Grassland Society No. 37, pp. 212-215.

D Hatch, A Joynes, A Stone & G Goodlass. (2004). Soil Fertility building crops in organic farming. 11th International Conference of the FAO ESCORENA Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture, Ramiran 2004, MURCIA SPAIN, October 6-9, 2004. pp 71-74.

S P Cuttle (2006). Development of the FBC model to estimate the nitrogen available from fertility-building crops in organic rotations. Making the most of soil nitrogen. Aspects of Applied Biology 79, What will organic farming deliver? COR 2006, pp. 259-262.

G Goodlass, D J Hatch, M A Shepherd, J A King, S P Cuttle, S Roderick & S Briggs (2006). Making the most of soil nitrogen. Aspects of Applied Biology 79, What will organic farming deliver? COR 2006, pp. 269-271.

Farming Press

Organic Studies Centre (2002). New Projects: The development of improved guidance on the use of fertility building crops in organic farming. In: Technical Bulletin 1, p. 9.

Organic Studies Centre (2003). Guidance on the Use of Fertility Building Crops. In: Technical Bulletin 2, p. 5.

Organic Studies Centre (2003). Advisory Leaflet: Soil Fertility Building Crops in Organic Farming. In: Technical Bulletin 3, supplement, pp.1-4.

Organic Studies Centre (2004). Factors Affecting Nitrogen Fixation by Red Clover. In: Technical Bulletin No.5, pp. 1-2.

Organic Studies Centre (2004). The supply of nitrogen from fertility building crops: results from monitoring of twelve organic farms. In: Technical Bulletin 6, pp. 1-3.

Organic Studies Centre (2004). Novel Crops. In: Technical Bulletin 6, pp. 3-4.

Organic Studies Centre, Technical Bulletin. Article describing the FBC model. *In preparation*

An article 'Soil Fertility Building Crops in Organic Farming' was published in the Soil Association's journal 'Organic Farming', Issue 80, winter 2003/04, pp. 22-23.

Additional Press coverage

West Briton, June 3, 2004
Western Morning News, July 21, 2004
Farmers Guardian, August 6, 2004
Farmers Guardian, September 10, 2004
BBSRC Journal (autumn 2004)