DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS **CSG 15**

Research and Development

Final Project Report

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Project title	Improving N use and performance of arable crops on organic arable farms using an expert group approach
DEFRA project code	**OF0178**
Contractor organisation and location	ADAS Consulting Ltd ADAS Boxworth, Boxworth Cambridge CB3 8NN
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Executive summary (maximum 2 sides A4)

Government seeks to support the development of organic farming in the UK, but nitrogen (N) almost always limits productivity on organic farms. This project devised guidance by which farmers could manage N to best effect on organic land. 'Experts' in i) organic farming systems, ii) manure management, iii) N cycling in farming systems and iv) crop N responses and N fixation, working through Case Studies representing arable and mixed organic systems and reviewing relevant literature, devised changes which would a) increase the availability of N for crop uptake, b) decrease losses of N to the environment, and c) be acceptable to farmers.

Nitrogen (N), phosphorus (P) and potassium (K) budgets were calculated for 9 organic Case Study farms in the UK. The farms were on sandy loam, silt clay loam and silt loam over chalk soil types and included stockless rotations and cattle, pig and poultry enterprises with a significant proportion of cropping. A soil surface nutrient budget was calculated for the target rotation on each farm using information about field management and measurements of the soil, crops and manure. Losses of N through leaching and volatilization were calculated independently using the NITCAT and MANNER models.

The rotations of the Case Study farms generally sustained total soil N, with only 2 of the 9 farms showing a small N deficit over the rotation. The ratio of N inputs supplied in the form of biological fixation : manure : atmospheric deposition was approximately 40:40:20 for stocked and 70:0:30 for stockless systems, demonstrating the importance of N deposited from the atmosphere to organic land. Averaged over the whole rotation, the size of the N inputs for non-leguminous crops were similar to those given to conventional crops. However, yields of these crops were only 50 to 80% of conventional yields. Levels of available soil N indicate that N must be a significant factor limiting productivity. Leaching significantly reduced N availability; of the total N input, 30-40% was leached. Inefficiency was also caused by manures being applied to the ley phase of the rotation, so that cash crops did not benefit. Finally, farmers often over-estimated the supply of available N

from grain legume crops. Mean wheat yield dropped from 6.0 t ha^{-1} after a forage legume to only 3.8 t ha^{-1} after a grain legume.

Of the 9 farms, 6 showed a P surplus and 3 showed a K surplus. Supplementary P fertilizer and additional feed for non-ruminant livestock caused the P surpluses. The stockless system without P fertilizer had a large P deficit. Stocked systems, which relied on recycling manure alone, had a small P deficit. Only rotations with a large manure return or imported feed showed a K surplus or a balanced K budget.

The budgets calculated for these Case Studies indicated no reason for organic systems to be inherently unsustainable with regard to N, P or K. Rotations showed a wide range of nutrient balances, with differences arising from contrasting crop sequences, varied interactions with on-farm livestock and use of supplementary nutrients. There is therefore scope to increase the efficiency of individual organic systems and minimise losses to the environment. Simple rotational budgets, as used in the Case Studies were found to be a useful tool for farmers and their advisors to understand and manage nutrient flows at a rotational level.

The literature review, done as part of this project and published in Soil Use and Management, Volume 18, indicated strongly that N in organically managed systems will restrict crop productivity, particularly of non legumes, by limiting the amount of available N during the period of rapid crop growth. This is due to a number of factors: 1) the large amount of available N released after cultivation of a ley declines substantially for the second and subsequent crops following the ley, 2) apart from vegetable residues, the amount of N made available to growing crops from incorporated cash crop residues is usually quite small, e.g. about 25 kg N ha^{-1} from field bean residues, 3) available N from organically produced manures tends to be less than in conventional systems; this is partly because of greater straw use and partly because composting, which is more frequent in organic systems, reduces the percentage of total N which is available for uptake by 10 to 50%.

The results of the Case Study analysis and literature review clearly showed that the supply of available N must be increased during the period of rapid crop growth to improve arable crop productivity in organic systems. The expert group identified the following strategies to help achieve this:

Minimise leaching

- delay ley incorporation and manure applications until late winter.
- establish a crop or cover crop no later than early autumn.

Improve manure N use

- Apply animal manures to arable crops, except where the grassland is deficient in P or K (<index 2).
- For best use of manure N make applications in spring at the start of rapid crop growth.
- The greatest yield increase will be gained by spreading a small amount of manure over a large area.
- Uncomposted manures contain most available N and will give the greatest crop response.

Matching crops with N availability

- Maximum use of legume N is ensured by minimising the time from incorporation to establishment of the next crop.
- Do not over-estimate N residues from grain legumes.
  - Where N availability is expected to be small, choose crops/cultivars with a small N requirement and a long period of N uptake, such as sugar beet and forage maize.

In conclusion, small improvements in efficiency of N retention, redistribution, or relocation were predicted to cause large improvements in output, since the greatest responses in crop production occur at the low levels of N common to organic systems. These improved management strategies were transferred to the organic farming community, through press articles and presentations to organic farmers, consultants and scientists.

Scientific report (maximum 20 sides A4)

OBJECTIVES & APPROACHES

Overall objective

To improve the performance of arable Organic cropping systems by identifying acceptable changes in practice which increase the availability of nitrogen for crop uptake and decrease losses of nitrogen to the environment.

Specific constituent objectives

1. To select between five and ten arable Organic farms which are appropriate for Case Studies and to quantitatively estimate nitrogen availability and nitrogen losses for representative rotations being used on these farms.
2. To identify aspects of these rotations for which N use and crop performance could be improved, to quantitatively estimate the degree of improvement in gross margins and N losses, and to develop these changes into a form which is acceptable to the farmers concerned.
3. To summarise for the wider Organic community the data and concepts that prove necessary to convince these farmers of the benefits of making the changes, and to transfer these data and concepts to consultants specialising in advising the Organic farming community, and to their clients.

The results are reported in three sections which relate to these three objectives. Section 1 describes nutrient budgets calculated for nine Case Study farms. Section 2 reports findings on whether the productivity of organic farms is restricted by the supply of available N. (These were prepared in the form of a literature review, which is due to be published in Soil Use and Management volume 18.) Section 3 identifies practices which limit arable crop performance due to the inefficient use of N and states strategies, which are acceptable to organic farmers, for increasing availability of N for crop uptake and reducing losses to the environment. Section 4 reports the technology transfer outputs and activities.

Approach

Our approach was to employ a small ‘expert group’, whose collective expertise embraces :

- Arable Organic farming systems: Isobel Wright (ADAS), Lois Phillips (EFRC) & Bill Cormack (ADAS)
- Managing N fixation by legumes: Roger Sylvester-Bradley (ADAS)
- Management of animal manures and organic ‘wastes’: Ken Smith (ADAS)
- Field management to restrict losses and optimise availability of N: Eunice Lord (ADAS)
- Crop management to maximise efficiency of N use: Roger Sylvester-Bradley (ADAS) & Pete Berry (Univ. Nottingham), and
- the skills of ‘message forming’ and giving on-farm advice.

This Group met at least twice per year, and their deliberations were supported by a post-doctoral research officer at the University of Nottingham for data collation, interpretation, drafting and reporting. A quantitative approach was essential; thus models developed for conventional agriculture were employed on specific questions, e.g. nitrate leaching. The work schedule was as follows:

Year One : Data acquisition and Case Studies

Case studies were set up relating to ten Organic farms, and data already available was augmented by visiting each farm to determine field information (soil types, cropping histories, grass management : grazing intensity, no. cuts, dates of cultivation, drilling and harvest for arable crops, animal manure inputs, estimated autumn crop cover, and crop type and performance) and farm information (potential sources of N, and attitudes and restrictions to innovations).

Estimates were then made for the most representative Organic rotation on each farm of N availability throughout each cropping season, and N lost as nitrate and ammonia from each rotation. These estimates were augmented by laboratory analyses of soil N, manure N or crop N.

Year Two : Synthesising improved strategies

The expert group explored alternative strategies with the aim of enhancing crop performance and / or restricting N losses from each case studied. Options included length and position of legume cropping, timings of cultivations, management of ley-arable relationships, management of manures, including possible manipulation of the composting process, management of manure applications, use of cover or catch crops, management of crop residues and manipulation of sowing and harvesting timings. These took into account the soils, climatic conditions, farm infrastructure and markets specific to each case studied. Using the same assumptions as those developed in 'Data acquisition' (Year One), the implications for N availability, crop performance and N losses were estimated for each case.

These findings were presented to a panel, formed from farmers from Case Study farms, its reaction was sought, and modifications were subsequently checked by consultation. The principle acceptable changes to organic arable systems were then summarised into 'messages', with the relevant considerations being itemised and illustrated so that they could be disseminated to and considered by organic advisers and producers.

Year Three : Technology transfer

Advisory aids were prepared, based on the assumptions used to formulate the acceptable improvements. These took the form of graphs and look-up tables for soil type and over-winter rainfall effects on leaching, N contents and N release properties of animal manures and waste organic materials, N release patterns from legumes, and N demands of various crops.

These were combined into a 4 page document, and published through 2 articles in the EFRC Bulletin in 2002. Additional opportunities were taken to present findings to the scientific community and organic farmers (see Section 4). A full day seminar (postponed due to the Foot & Mouth Epidemic in 2001) is to be held at HDRA in August 2002 for consultants from EFRC, the Soil Association and other organisations.

SECTION 1: N, P & K BUDGETS FOR CASE STUDY FARMS

The aim of this part of the project was to compile N budgets for typical ley/arable rotations on organic farms in the UK. Data was compiled so that P and K budgets could also be calculated, to make an assessment of the sustainability of organic farming systems (P&K data were also made available to DEFRA Project OF0114).

Sites

Nine organic farms in the UK, which had been fully certified for >5 years, and which had a significant proportion of cropping in their rotation were chosen (Table 1). The soil types included sandy loam, silt clay loam and shallow silt loam over chalk. The predominant stock used on the farms were dairy cattle (Rotations 1 & 3), beef cattle (2 & 9), outdoor pigs (4 & 6) and poultry (7), and two additional farms were stockless (5 & 8). The target rotation for each farm was identified with the farm manager; this rotation will not necessarily be adhered to across the whole farm in every season, but represents the target rotation for the farm over a number of seasons. For each farm, a set of fields was identified representing each phase of the rotation in the year of sampling (1998-1999). Field management information for this and a number of previous seasons was compiled through interviews with the farm manager and from documented farm records. Between 2 and 5 years of management information was collected for each field (Table 2).

System definition and approach used to calculate nutrient budgets
A nutrient budget was calculated for each field. The system was defined as the cropped area to the maximum rooting depth (Figure 1). This type of budget is sometimes known as a soil surface budget. Nutrient inputs were from N fixation, atmospheric deposition, fertilizing materials, manure and seed. Nutrient outputs were through off take in crop products and animal products, volatilization and leaching. Livestock were outside the system, but interacted with it through returns in manure (including both applied manure and excretal returns during grazing) and through animal off take of herbage during grazing. Outdoor pigs interacted with the system less than ruminant livestock because they relied on external feeds. Their net contribution of nutrients to the soil was in excretal returns. For this reason the nutrient off takes in animal products was not calculated for outdoor pigs. Nutrient budgets were thus compiled for each field for all years with available information. The nutrient budget for each phase of a rotation was averaged over all years and compiled on a per hectare basis to give the average nutrient budget for the whole rotation.

Quantification of inputs and outputs
N fixation by leguminous crops, free-living bacteria and nutrient inputs through atmospheric deposition were estimated using data from the literature (Table 3). Manure and any other composted waste samples were collected on most of the farms, taking care to obtain representative quantities of material (Table 2); total N was determined on fresh samples by wet oxidation (Kjeldahl method) to avoid N losses by volatilization during drying. Nutrient inputs in fertilizing materials and manure were therefore calculated from the measured N contents and application rates. For P and K and in the few cases where the N content had not been measured, estimated nutrient contents were used (Table 3). Excretion by outdoor pigs was estimated using the number of animals, age, duration in a field and the amount and type of feed (Smith *et al*. 2000). The feed conversion figures under conventional management were reduced by 20% to account for extra maintenance requirements, which meant that greater manure N was produced for the amount of feed N consumed compared with conventionally reared pigs. Nutrient inputs in seed were estimated from drilling rates and estimated nutrient contents (Table 3).

Crop samples were taken from 18 fields under cereal cropping at the 1999 harvest. Samples were dried and ground before analysis for total N content by combustion (Leco CN analyser). No analyses of P and K contents were made. The nutrient off take of crops was calculated from the crop yield and its measured N content. For P and K and where measurements of N content were not made, assumptions given in Table 3 were used. Estimates of the amount of N exported by cattle during the grazing period as saleable produce (milk and meat) or lost by volatilization during grazing were based on work done on conventional farms (Jarvis 1993; Scholefield 1991; Sommer & Hutchings 1997; Table 3). The amount of N lost due to leaching was calculated using the NITCAT model (Lord 1992). This model estimates the amount of potentially leachable N based on the previous crop, modified according to the balance between N inputs and off takes. The resulting potential leaching load is further modified according to N inputs in the autumn, mineralization of N residues from previous years and autumn N uptake. The actual amount of N that leached depended on the amount of drainage, which was calculated using IRRIGUIDE (Bailey & Spackman 1996) from inputs of soil type, crop cover and weather. The MANNER model (Chambers *et al*. 1998) was used to calculate the amount of manure N volatilised as ammonia after application. This depended upon the amount of available N in the manure, how quickly it was incorporated after application and, for slurry, whether or not it was injected. The amount of available N in the manure was either measured or a standard value for organically produced manures was assumed (Table 3).

Soil samples were taken from each field to a depth of 90 cm or to the bed rock. The samples were refridgerated and analysed for total N, NH_4-N and NO_3-N. A soil bulk density of 1.3 g cm^{-3} was assumed to convert the percentage N in the soil to kg N ha^{-1}.

Table 1 Basic farm information and the crop sequence in the target rotation at each site.

Farm/rotation number	Soil type	Livestock enterprise	Rotation
1	SZL	Dairy	Ley, Ley, Ley, Beet, SB, WT
2	ZCL	Beef	Ley, Ley, Ley, WW, WT
3	SL	Dairy	Ley, Ley, Ley, WW, WT
4	caZL	Pigs/ sheep	Ley, Ley, WW, SC, Pigs, WW
5	ZCL	None	RC, WW, SB, SC
6	ZCL	Pigs	Ley, Ley (pigs), WW, SW, WC
7	SL	Chickens	Ley, Ley, WW, WO, WB, WW, Sba
8	ZCL	None	RC, Pots, WW, SB, SW
9	caZL	Beef/ sheep	Ley, Ley, Ley, WW, WO, WB, WW, SO

Soil types: ca – calcareous; C – clay; L – loam; S – sand; Z – silt.
Crops: Beet – fodder beet; Ley – white clover / ryegrass ley; Pigs – pigs on stubble; RC – Red clover; SB – spring beans; Sba – spring barley; SC – spring cereal; SO – spring oats; SW – spring wheat; WB – winter beans; WC – winter cereal; WO – winter Oats; WW – winter wheat; WT – winter triticale.

Table 2. Summary of the field management information collected at each farm.

Farm/rotation number	Years of data	Cultivations (+ dates)	Sowing date	Seed rates	Establishment	Cultivar	Over winter crop cover	Proportion of clover	Saleable crop yield	Crop residue yield	Saleable crop N content	Pest information	Yield limiting factors	Periods with livestock	Livestock stocking rates	Amount of feed provided in field and its N content	Manure applications (type, date. amount. incorporation)	Manure N analysis
1	3	✓	✓	✓	✓	✓	*	*	✓	*	*	✓	✓	✓	✓	N/A	✓	✓
2	2	✓	✓	✓	*	✓	*	*	✓	*	*	✓	✓	✓	✓	N/A	✓	*
3	4	✓	✓	✓	✓	✓	*	*	✓	✓	✓	✓	✓	✓	✓	N/A	✓	✓
4	5	✓	✓	✓	*	✓	*	*	✓	*	✓	✓	✓	✓	✓	✓	N/A	✓
5	2	✓	✓	✓	✓	✓	*	N/A	✓	*	✓	✓	✓	N/A	N/A	N/A	N/A	N/A
6	2	✓	✓	✓	✓	✓	*	*	✓	*	✓	✓	✓	✓	✓	✓	✓	✓
7	2	✓	✓	*	*	✓	*	*	✓	*	✓	✓	✓	✓	✓	✓	✓	*
8	5	✓	✓	✓	✓	✓	✓	N/A	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A
9	2	✓	✓	✓	*	✓	*	*	✓	*	✓	✓	✓	✓	✓	N/A	✓	✓

✓ Exact information obtained
* Estimates made from observation or other information
N/A Not applicable

Figure 1. Conceptual system showing the inputs and outputs of nutrients (N, P & K) used for calculation of the nutrient budgets of the rotation. The livestock (even while grazing) are considered to be outside the rotation system and interact with the rotation through the returns of manure and by utilisation of the pasture/stubble

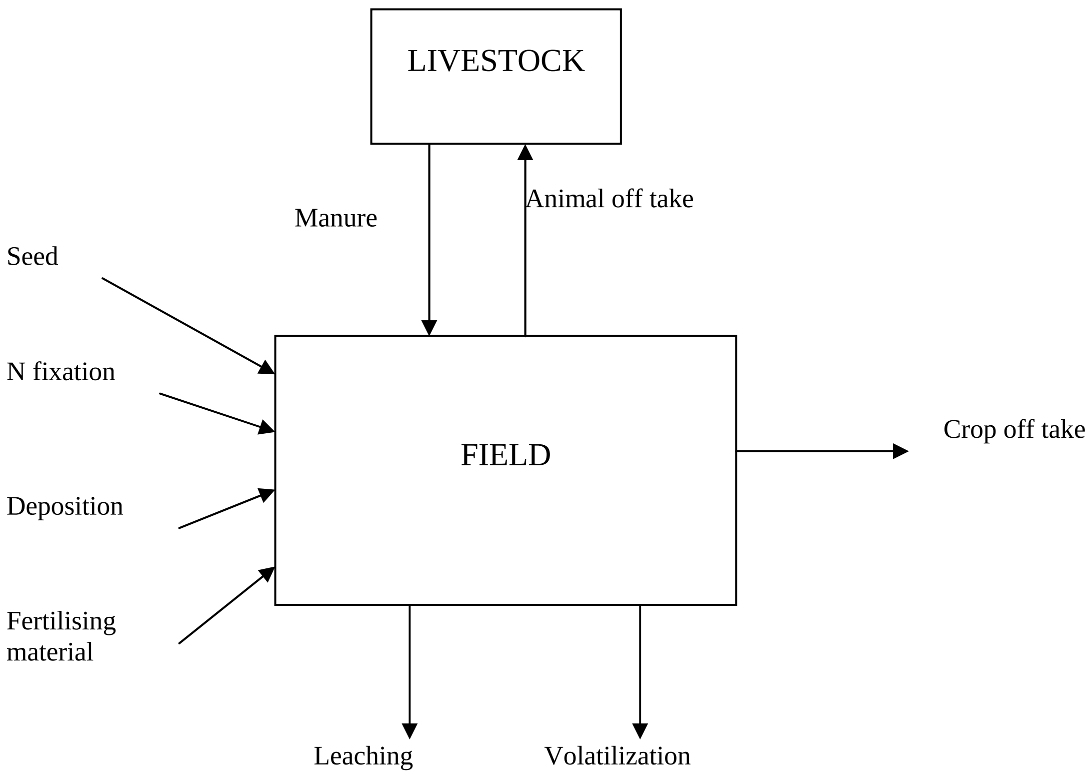

Table 3. Assumptions used to calculate inputs and outputs to nutrient budgets

Input/output	N Value	P value	K value	Source
N fixation				
1–2 year old white clover ley (*Trifolium repens*)	150 kg N ha^{-1} yr^{-1}	-	-	Kristensen *et al.* (1995)
>2 year old white clover ley	85 kg N ha^{-1} yr^{-1}	-	-	Kristensen *et al.* (1995)
Red clover (*Trifolium pratense*)	240 kg N ha^{-1} yr^{-1}	-	-	Schmidt *et al.* (1999)
Spring/winter beans *(Vicia faba)*	200 kg N ha^{-1} yr^{-1}	-	-	Kopke (1987),
Spring/winter bean residue after grain harvest	25 kg N ha^{-1} yr^{-1}			Sylvester-Bradley & Cross (1991)
Free living soil bacteria	5 kg N ha^{-1} yr^{-1}	-	-	Goulding (1990)
Atmospheric deposition				
Close to urban areas	40 kg N ha^{-1} yr^{-1}	~0.5 kg P ha^{-1} $year^{-1}$	-	Goulding *et al.* (1998a,b)
Rural areas	30 kg N ha^{-1} yr^{-1}	~0 kg P ha-1 $year^{-1}$	-	Goulding *et al.* (1998a,b)
Areas unaffected by sea spray			~3 kg K ha^{-1} $year^{-1}$	NEGTAP, 2001
Manures				
Cattle FYM	5.2 kg N t^{-1} (fwt)	1.1 P t^{-1} (fwt)	5.5 K t^{-1} (fwt)	Shepherd *et al.* (1999)
Cattle slurry	2.5 kg N m^{-3}	0.42 P m^{-3}	2.1 K m^{-3}	Shepherd *et al.* (1999)
Poultry (layer) manure	16 kg N t^{-1} (fwt)	4.5 P t^{-1} (fwt)	6.0 K t^{-1} (fwt)	Anon. (2000)
Crop nutrient content				
Wheat (*Triticum aestivum*) grain (100% dwt)	1.7%N	0.3%P	0.5%K	OF0178
Wheat straw (100% dwt)	0.46%N	0.1%P	0.8%K	OF0145
Spring/winter beans (100% dwt)	3.4%N	0.5%P	1.0%K	OF0145
Barley (*Hordeum vulgare*) grain (100% dwt)	1.3%N	0.3%P	0.5%K	OF0178
Oat (*Avena sativa*) grain (100% dwt)	1.6%N	0.3%P	0.5%K	OF0178
Triticale (*Tritiosecale*) grain (100% dwt)	1.5%N	0.4%P	0.5%K	OF0178

Triticale whole crop silage (100% dwt)	1.6%N	0.3%P	2.0%K	Alderman & Cottrill (1995)
Grass/clover silage (100% dwt)	2.7%N	0.3%P	2.1%K	Alderman & Cottrill (1995)
Fodder beet (*Beta vulgaris*) (100% dwt)	1.0%N	0.1%P	0.6%K	Alderman & Cottrill (1995)
Potatoes (*Solanum tuberosum*) (100% dwt)	1.4%N	0.1%P	0.6%K	OF0145
Livestock				
Milk off take during grazing	19 kg N ha^{-1} yr^{-1}	3.0 P ha^{-1} yr^{-1}	5.5 K ha^{-1} yr^{-1}	Jarvis (1993)
Cattle growth during grazing	14 kg N ha^{-1} yr^{-1}	4.1 P ha^{-1} yr^{-1}	1.0 K ha^{-1} yr^{-1}	Jarvis (1993)
Cattle gaseous losses during grazing	11 kg N ha^{-1} yr^{-1}	-	-	Scholefield (1991), Sommer & Hutchings (1997)

OF0178 – mean of measurements taken in DEFRA project No OF0178, OF0145 – mean of measurements taken in DEFRA project No OF0145

RESULTS

N

The N budgets on seven of the nine case study farms showed surpluses (18 to 64 kg N ha^{-1} year^{-1}), and two showed deficits (-15 and -19 kg N ha^{-1} year^{-1}) (Table 4). In the few other N budget studies that have estimated losses in organic rotations, balances ranged from -38 to 30 kg N ha^{-1} year^{-1} (Nolte & Werner 1994; Kaffka & Koepf 1989). When leaching and volatilization are estimated independently of the N budget, the surplus/deficit estimates the impact of farm management on the long-term accumulation or depletion of soil N content. This indicates that the majority of organic rotations in this study are probably sustainable in terms of N and may even build soil N content in the short-term. Soil measurements on the farms, which had been converted for 10 or more years, had high total N contents of 15 to 17 t ha^{-1} (to bed rock or 90cm depth). N budgets in deficit (8 and 9) appeared to be linked with rotations containing grain legumes, whose grain was harvested, and which were followed by one or two cereal crops. Harvested grain legumes are expected to leave a residue worth only 25 kg N ha^{-1} to a following crop (Table 3), which would mean that following cereal crops would have to rely on N supply by mineralization from the soil and older, and more recalcitrant, crop and manure residues. Mean wheat yields in Rotations 8 and 9 provide some evidence for this. In these rotations the mean wheat yield dropped from 6.0 t ha^{-1} after a forage legume to only 3.8 t ha^{-1} after a grain legume. The total soil N content of Rotation 9 (converted for >10 years) was 12 t ha^{-1}, compared with 15 to 17 t ha^{-1} for the case studies with a positive N balance, indicating that this rotation is more exploitative of N. It should be noted however, that the N balances estimated for the two rotations with the most positive and negative N balances would have to continue for 30-40 years to produce a 3 t ha^{-1} difference in total N.

The stocked organic systems relied on biological fixation for 42% (range of 35 to 46%) of their N inputs, with manure accounting for 35% (26 to 45%) and atmospheric deposition 22% (13 to 26%). Some of the manure N returned to these rotations was derived from the N fixed by silage crops fed to stock over-winter. Stockless systems relied almost completely on biological fixation (70%) and atmospheric deposition (27%) for their N inputs. While biological fixation of N is the driving force of the rotational N cycle, as might have been expected, atmospheric deposition of N is also a key source of N in both systems. The mean N input for crops which export produce from the field, e.g. cereals, grain legumes and silage, ranged from 150 to 300 kg N ha^{-1}. This is similar to the amounts of N supplied to non-leguminous crops in conventional systems (Anon, 2000). However, not all of this N input would have been available for crop off take. Factors controlling the supply of available N in organic systems are discussed by Berry *et al.*(2002).

N outputs resulted mainly from crop off take and leaching. However, the size of these two outputs was heavily influenced by the intensity of animal production and soil type. The low intensity animal production systems included the stockless rotations (5, 8), the beef systems (2, 9) and the sparsely stocked outdoor pigs (6). These had an average N input of 155 kg ha^{-1}yr^{-1} and an average N output of 141 kg N ha^{-1}yr^{-1}. The higher intensity systems included the dairy systems (1,3), the densely stocked outdoor pigs (4) and poultry (7). These had an average N input of 191 kg ha^{-1}yr^{-1} and average output of 155 kg ha^{-1}yr^{-1}. The low intensity systems had a greater proportion of N outputs as crop off take (59% on average) compared with leaching (31%). Volatilization outputs averaged 3%, but could amount to 10% where manure was not incorporated quickly. The high intensity systems had a greater proportion of N outputs as leaching (41%) compared with crop off take

(31%). Predictably, outputs as animal products and volatilization were greater than in the low intensity stocked systems. It therefore appears that efforts to increase animal production result in quantitatively and proportionately more N being wasted through leaching and volatilization. This might be expected because the inefficient process of converting atmospheric N to animal products via numerous cycles of forage plant growth, grazing and excretion means that N will be more at risk to leaching and volatilization than with crop production alone. However, this is difficult to demonstrate conclusively with these case studies because the high intensity systems were also generally on soil types more at risk of leaching.

The largest source of error within the N balances was from quantifying biological fixation. The range of biological fixation is reviewed by Watson *et al.* (2002), e.g. a 1 to 2 year old white clover ley could fix 50% more or less than assumed in Table 3. This variability is not large enough to alter the general conclusions drawn from the studies, but means that small differences must be interpreted with care. This highlights the need to develop more precise methods of quantifying the effects of legume species, soil pH, soil available N etc. on N fixation. Manures are often a large source of error in N budgets, but this has been minimised in this study through measurement. NITCAT was developed to estimate leaching under conventionally managed systems, but was able to accommodate organic systems because it had been based on much information without use of N fertilizer and measured values of soil organic matter were used for estimating rates of mineralization. Nitrous oxide losses from the soil were not considered within the N budgets. However, these have been estimated to be negligible in grassland when applications of inorganic fertilizer were less than 100 kg N ha^{-1} (Scholefield *et al.* 1991) and to only amount to losses of between 1 and 3 kg N ha^{-1} year^{-1} in conventionally managed arable systems with sand loam or silt clay loam (Webb *et al.* 2000). Volatilization from cut and mulched grass clover ley were found to be only 0.2 kg N ha^{-1} year^{-1} by Schmidt *et al*. (1999) and are therefore assumed to be negligible in these N budgets. This study has shown that N budgets should be calculated using crop N contents of produce from organic farms rather than conventional farms, e.g. the average N content of conventionally produced wheat, barley, oats and potatoes (Alderman & Cottrill, 1995) was about 20% greater than in organic crop produce (data from this study and W. Cormack *pers. comm…*).

P

The P budgets on 6 of the case study farms showed a surplus (6 to 34 kg P ha^{-1} year^{-1}) while 3 had deficits (-1 to –8 kg P ha$^{–1}$ year^{-1}). Farm scale budgets have measured a similar range of balances (-1 to 23 kg P ha$^{–1}$ year^{-1}) (Hermansten & Kristensen 1998; Cuttle & Bowling 1999). Since P flows in rotational systems are quantitatively much lower than those of N (average outputs of 14 kg P ha $^{–1}$ year^{-1} in this study), these small deficits may have a significant impact on the sustainability of the system even in the medium term. However, in most cases the use of supplementary P fertilising materials (in 5 rotations), corrected any potential P deficit. The large P surplus (34 kg P ha^{-1} year^{-1}) in Rotation 1 would be removed if the supplementary P fertilizer (33 kg P ha^{-1} year^{-1}) currently used was withdrawn from the system. In Rotations 4 and 7 the use of supplementary feed for the non-ruminant livestock may have caused the P surpluses (24 and 7 kg P ha^{-1} year^{-1} respectively), even in the absence of supplementary P. However, imported feed was not accounted for directly in these rotational budgets. Whether or not weathering processes of the soil are sufficient to match any net export of P within a rotation depends upon soil type. The P content in the upper 5cm of a sandy soil in the Netherlands under a silaged grass/clover ley fell by 25% over 5 years, even when manure was applied (Younie & Baars 1997). However on a non-sandy soil, an annual P deficit of 2 to 4 kg P ha^{-1} caused no decline in the content of extractable P over 10 years (Kaffka & Koepf, 1989).

K

None of the rotations received any supplementary K fertilizer, though some of the inputs of supplementary P contained small amounts of K. The K budgets on 3 of the case study farms showed a surplus (9 to 28 kg K ha^{-1} year^{-1}), one was perfectly balanced (rotation 7) and 5 rotations showed K deficits (-21 to –52 kg K ha^{-1} year^{-1}). Both Rotations 1 and 4 received substantial inputs of slurry to the rotation which returned more K to the rotation than was removed. This is possible because the livestock on both of these farms were fed with imported concentrates. In the other livestock rotations inputs of K via manure were not sufficient to balance the removal in silage and other crops (except Rotation 7). However, K leaching was not estimated and this may represent a significant output of K from the system. The leaching of K from manure heaps during storage has been found to be particularly high. Godden & Penninckx (1997) reported values from a number of studies showing losses during composting from 18 to 67% of the original K content. The stockless rotations had the largest K deficits at up to –52 kg K ha^{-1} year^{-1}. Other studies have shown that livestock only farm budgets are often positive for K (e.g. Cuttle & Bowling 1999), with mixed farms more likely to have negative balances (Nolte & Werner 1994). As with P, the ability of any deficits to be compensated through weathering of mineral reserves depends upon soil type. Some soils in the UK can supply up to 40 kg K ha^{-1} year^{-1} (Goulding & Loveland 1990). However, the K content of sandy soils has been shown to decrease by 62% within 3 years under a silaged grass/clover ley (Younie & Baars 1997). In general, K deficits of greater than 25 kg K ha^{-1} year^{-1} in any rotation should be a matter of concern (particularly here in rotations 8 and 9) and soil K level should be carefully monitored, so that depletion of soil reserves can be prevented.

Table 4. Average N, P and K budgets (kg ha^{-1} year^{-1}) for nine case study rotations calculated for a complete rotation. The assumptions used for the quantification of inputs and outputs calculations are described in the text.

Farm/rotation	1			2			3			4			5			6			7			8			9		
Stock	DAIRY			BEEF			DAIRY			PIGS			NONE			PIGS			POULTRY			NONE			BEEF		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
Inputs																											
Biological fixation	98			81			77			73			110			60			71			76			73		
Manure	94	19	96	67	8	39	55	9	58	96	31	43				59	14	29	41	18	37				42	8	43
Deposition	30	0	3	40	0.5	3	40	0.5	3	40	0.5	3	40	0.5	3	40	0.5	3	40	0.5	3	30	0	3	40	0.5	3
Seed	2	0.5	1	2	0.5	0.5	2	0.5	0.5	2	0.5	0.5	3	0.5	1	2	0.5	1	4	1	1	5	2	4	3	0.5	1
Fertilising material		33	0.5		12	0		0	0		0	0		0	0		7	0		0	0		14	0.5		16	0
Outputs																											
Crop off take	47	17	85	84	13	64	63	11	51	33	6	19	76	9	25	77	15	60	81	12	41	88	17	60	113	18	82
Animal off take	15	2	2	6	2	0.5	11	2	2										2	0.5	0				3	1	0.5
Leaching	75			39			59			136			49			49			50			38			58		
Volatilization	23			11			10			13			0			12			5						3		
Balance	64	34	14	50	6	-22	31	-3	9	29	26	28	28	-8	-21	23	7	-26	18	7	0	-15	-1	-52	-19	6	-35

MAIN FINDINGS

- **Of the 9 case studies, 7 had a positive N balance, 6 had a positive P balance and 3 had a positive K balance. The degree to which a particular nutrient was in surplus or deficit appeared to be independent of the balance of the other nutrients within the rotation.**
- **The ratio of N inputs supplied in the form of biological fixation : manure : atmospheric deposition was approximately 40:40:20 for stocked systems and 70:0:30 for stockless systems. This emphasises the importance of the N supplied by atmospheric deposition.**
- **Averaged over the whole rotation, the N input for each crop which exported produce from the field, e.g. cereals, grain legumes and silage, ranged from 150 to 300 kg N ha^{-1}. This is similar to the amounts of N supplied to non-leguminous crops in conventional systems (Anon., 2000)**
- **30-40% of the N fixed by legumes, deposited from the atmosphere or inputted in the form of manures is leached.**
- **The majority of manure is applied to the ley phase of the rotation.**
- **Supplementary P fertilizer and additional feed for non-ruminant livestock caused the surplus P balances. Stockless systems without fertilizer had a large P deficit and stocked systems which relied on recycling manure alone had a small P deficit.**
- **Only rotations with a large manure return or brought in feed had a positive or neutral K balance. This is likely to be reduced if K leaching from manure had been estimated. The sustainability of the rotations in K deficit will depend on the ability of the soil to supply K by weathering of soil mineral reserves.**

- **Bought-in manures and feeds on organic farms must be from other organic farms. So stockless farms e.g. Terrington, export nutrients to livestock-based farms. There will be a net loss of K and P from organic farms as a whole, and there is a need for available and cost-effective supplies of these nutrients. Project OF0114 deals with this issue.**
- **The budgets calculated for these case studies indicate that there is no reason why organic rotations should be inherently unsustainable with regard to N, P or K. The rotations show a wide range of nutrient balances and the differences arise from the contrasting rotations, varied interactions with on-farm livestock and use of supplementary nutrients. There is therefore scope for individual organic farms to increase the efficiency with which they use nutrients within the rotation to minimise losses to the environment.**
- **Simple rotational budgets, as used in the case studies, are one tool to enable an increased understanding of nutrient flows at a rotational level by organic farmers and their advisors.**

SECTION 2: IS THE PRODUCTIVITY OF ORGANIC FARMS RESTRICTED BY THE SUPPLY OF AVALIALBLE N?

The literature review done as part of this project and published in Soil Use and Management 18, showed that organic farming systems have the potential to supply a large amount of available N to growing crops, through the incorporation of crop residues (Table 5) and manures and composts (Table 6), but that this is not achieved frequently enough. The incorporation of leguminous crops can release about 150 kg ha^{-1} of mineral N within a 3-month period. Clover can supply more than 100 kg N ha^{-1} yr^{-1} to companion grasses in a mixed sward. Vegetable crops could be expected to contribute more than 50 kg N ha^{-1}, which may be mineralised within one month of incorporation. Applying uncomposted FYM at 25 t ha^{-1} could provide over 30 kg of immediately available N ha^{-1}, with a further 35 kg mineralised within 6 months. Unfortunately these levels of available N are rarely achieved in practice and the timing of mineralization is often not synchronised with crop demand. The large amount of available N released after cultivation of a ley declines substantially for the second and subsequent crops following the ley. Apart from vegetable residues, the amount of N made available to growing crops from incorporated cash crop residues is usually quite small, e.g. about 25 kg N ha^{-1} from field bean residues. This is because these residues often have a relatively high C:N content, causing slow mineralization and poor synchrony with the 3- to 6-month period of rapid crop growth. Available N from organically produced manures tends to be less than in conventional systems; composting, which is more frequent in organic farming (Shepherd *et al.* 1999), further reduces the percentage of total N which is available for uptake by 10 to 50%. For example, 25 t ha^{-1} of organically produced and composted cattle manure may provide only 6 kg of N ha^{-1} that is immediately available for crop uptake, with a further 12 kg mineralised within 6 months. In comparison to these organic inputs, fertilizer applications on conventional farms typically supply 100 to 250 kg N ha^{-1} to arable crops and up to 350 kg N ha^{-1} to grassland (Anon. 2000).

Evidence that available N is restricting productivity can be inferred from the low N contents of organically grown cereal grains. Research with conventionally grown winter wheat has revealed a reliable relationship between the grain N content and the supply of available N (G. Goodlass *pers. comm.*.). The concentration of grain N which coincided with the lowest N supply giving the maximum yield was stable at about 2.2%. Figure 2 shows how the percentage of N in the grain and grain yield both decrease with smaller applications of inorganic fertilizer in the spring. The grain N content of organically grown bread making wheat varieties has been shown to average 1.75% (1.5 to 1.9%) (Gooding *et al.* 1999). Conventionally produced bread making wheats have a grain N content of 2.2 to 2.3%. This indicates that the N supplies to these organic crops were generally small compared with conventionally grown wheat, and that large yield benefits could be realised by increasing the supply of available N. It should be noted that greater N supplies also increase the risk of lodging and disease. However, for many organically grown crops, there appears to be scope for moderate increases in N supply without reaching the high levels of N supply where the yield benefits are outweighed by yield losses induced by lodging and foliar disease (Berry *et al.* 2000; Bryson *et al.* 1997).

Table 5. Estimates for the total N and plant available N in crop residues.

Crop residue	Total N (kg N ha^{-1})	Plant available N after incorporation (kg N ha^{-1})	Months after incorporation
[c,o] >2yr old white clover ley	300	150	3 (autumn)
[o]6 mnth old grazing rye	130	100	3 (spring)
[c*] Cauliflower/brussels	60	50	1 (summer)
[c] Peas/beans	80	25	12
[c] Barley/oats/wheat	25-50	1-10	12

[c] – Conventional data; [o] – organic data; * - No inorganic fertilizer used.

Table 6. Estimates for the total N and plant available N in manures and compost at typical application rates.

Manure	Application rate (t or m^3 ha^{-1})	Total N (kg N ha^{-1})		Plant available N (kg N ha^{-1})	
		Conv.	Org.	Conv.	Org.
Fresh cattle FYM	25	150	125	38	14
Stored cattle FYM (>6 months)	25	150	125	15	6
Cattle slurry	25	75	63	38	22
Poultry	10	160	-	80	-
Composted green waste	10	120		1-8	

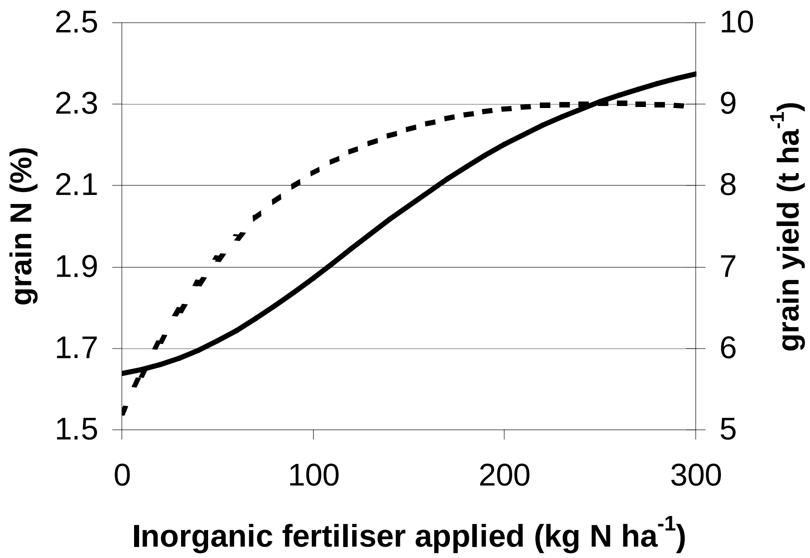

Figure 2. Relationship between amount of inorganic fertilizer applied in spring and grain N % (100% dry matter) (—) and grain yield (85% dry matter) (---) for 17 crops of milling winter wheat on clay soil (G. Goodlass, pers.comm..).

MAIN FINDINGS

- **The literature provides strong evidence that arable crop production in organic systems will be restricted by limited amounts of available N during the 3-6 month period of rapid plant growth.**
- **The low protein content of organically produced cereal grains is further evidence that the supply of available N is small.**

- **N availability is small in organic systems because:**
  1. **legumes are incorporated infrequently**
  2. **manures contain less N than conventional manures and this slows their mineralization after incorporation into the soil.**
  3. **composting is practised more frequently, which reduces the mineral N content of manures.**
  4. **crop residues usually have a low N content and wide C:N ratio which slows their mineralization after incorporation.**
- **Organic farmers over-estimate the supply of available N after grain legumes such as beans and peas. This is evidenced by low cereal yields after winter beans.**

SECTION 3: MANAGEMENT STRATEGIES FOR INCREASING AVAILABILITY OF N FOR CROP UPTAKE AND REDUCING LOSSES TO THE ENVIRONMENT

The expert group identified three general areas where N use could be improved: 1) reducing leaching, 2) better use of manure N and 3) matching crops with N availability. This section discusses how organic farmers could improve each of these areas.

Reducing leaching

The N budgets on case study farms showed that about 30-40% of N inputs were leached on the ley/arable farms; making more of this N available for crop uptake must be a target. Most leaching occurred during the winter after incorporation of a ley in the autumn. Measurements and calculations showed that the amount of mineral N in the soil during November, after ley incorporation between September and October, was about 140 kg N ha^{-1}. Much of this was expected to leach over winter because any crop established later in the autumn had neither the time nor the size of root system to immobilize the available N. Delaying the incorporation of the ley until later in the autumn will reduce mineralization. For example, delaying incorporation of pea residues from late July until early September reduced the amount of soil mineral N in autumn by 35% (Stokes *et al.* 1992). It is likely, then, that incorporating the ley in late winter or early spring and growing a spring sown crop would reduce the amount of N lost to leaching, thus increasing availability for crop uptake. Spring incorporation may result in slightly less mineralization due to cooler temperatures and a wider C:N ratio of the residues, but a significant supply of available N would be expected for the cash crop. Henrikson *et al.* (2000) showed that spring incorporation of a ley provided a better synchrony of N release with crop demand compared with autumn incorporation. In conventional systems spring cereals yield less than winter cereals. However in an organic system, it seems possible that spring sown cereals with a larger supply of N may yield better than autumn sown crops with a small N supply. However, it is more difficult to produce a seedbed with a small aggregate size, which is required for the successful establishment of crops with small seeds, after incorporating leys in the spring (Stopes *et al.* 1996). Spring incorporation will seldom be possible on the 30% of UK soils with a high clay content, but should usually be achievable on the remaining soil types (Clarke 1999). There is some evidence that incorporated residues can reduce establishment via allelopathic effects (Barnes & Putnam 1986), and a further potential problem is the risk of leaching during the following winter (Lord *et al.* 1997). This could be minimised by establishing the following crop early in autumn to maximise N uptake during autumn. Incorporation of a residue with a wide C:N ratio, such as cereal straw, is also likely to minimise leaching by immobilizing mineral N (Jenkinson 1985). On livestock farms, however, straw is more likely to be utilised as bedding.

Better use of manure N

The common practice of applying manures and composts to the forage legume phase of the rotation (Shepherd *et al.* 1999) means that non-leguminous crops cannot benefit from the supply of manure N. Mineral N from manures also suppresses N fixation by the forage legumes. The rationale behind applying manures to forage legumes is to increase the supply of soil phosphorus (P) and potassium (K) to meet the potentially large demand for silage production and to maintain the clover population. Recent experiments by Baars (2000) compared the effect of slurry and FYM applications (containing N, P and K at 130, 25 and 200 kg ha^{-1} respectively), with equivalent applications of inorganic P and K fertilizer, on the yield of a grass clover ley. This showed that the slurry and FYM applications increased the dry matter yield of the grass clover mix by 10%, had no effect on the total N content of the sward and reduced the dry matter of the white clover by 30%. The N fixed from the atmosphere was effectively exchanged for manure N when slurry and FYM were added, which means that the manure N was wasted.

This presents a dilemma: how to provide the clover with adequate P and K without reducing its N fixing potential by adding too much available N. Phosphorus and K indices of between 1 and 2 are required to maintain clover (Thomas *et al.* 1991). In conventional systems, silage yield responses to K are only observed on soils with a K index of 0 or 1 (Webb *et al.* 1990). Regular inputs of P and K will be required on sandy soils to maintain P and K indices of 1 or 2. These could be supplied as compost for which P and K availability is high, but N availability is low. However, on other soil types, which comprise about 70% of mixed arable land in the UK (Clarke 1999), maintenance amounts of P and K could be applied at any time during the rotation. This assumes that there is not a significant amount of luxury uptake of K by the crops. Therefore, on certain soils there appears to be potential for transferring some of the manure from the forage legume to the cash crop. Applying manures to arable land would also provide opportunities for rapid incorporation to reduce volatilization losses. Uncomposted manure, which is permitted by the organic standards, would give the greatest yield response because it contains more available N than composted manure (Kirchmann 1989; Sommer 2001). The benefits of composting manures to destroy weed seeds and pathogens must be balanced against the reduction in mineral N content.

Modest yield improvements across the farm would be expected when small amounts of manure are applied to a large area as opposed to a large amount of manure to a small area. This is due to the diminishing response of yield to N supply (Figure 2). For example, we estimate that the spring application of poultry manure to a cereal crop at a rate of 10 t ha^{-1} (160 kg total N ha^{-1}) would increase yield by 2.0 t ha^{-1}. Applying ¼ of this rate would increase yield by 0.7 t ha^{-1}, but could be spread over four times the area, giving a yield advantage of 0.2 t ha^{-1} over the whole cereal area. The net benefits of this practice must be balanced with the greater application costs. Potential problems with applying manure to spring arable crops include the greater risk of soil compaction and uneven manure spreading.

Matching crops with N availability

It seems likely that alterations in farm management can improve the amount and synchrony of N availability for organically grown crops. The nature of N sources in organic systems (low available N content and slow mineralization) mean that the amount of available N which can be supplied to a crop, during its main growth period, will generally be limiting. Although organic rotations are generally designed so that more N-demanding crops are grown following the ley phase, when the N supply is greatest, there is a need to further tailor crops to suit the N dynamics of organic systems. Crop species with a long period of N uptake, such as potatoes and sugar beet, can make better use of the slow but prolonged release of available N. Crop species with a smaller requirement for N such as forage maize (Zea mays) or sugar beet could be advantageous. Acquisition of N may be improved by using species or cultivars with root systems better able to intercept and take up soil N. For example, deep rooted species, such as chicory, may increase N uptake, and significant differences have been found for the ability of winter wheat cultivars to take up soil mineral N (Foulkes *et al.* 1998; Le Gouis *et al.* 2000). Future improvements in N utilisation within organic systems could be realised by breeding crops with traits that improve the capture of available N and the efficiency with which it is converted to yield.

MAIN FINDINGS

- **Minimise leaching:**

1. **delay ley incorporation and manure applications until late winter (however, this may increase leaching risk the following year).**
2. **establish a crop or cover crop no later than early autumn. (however, autumn-sown crops cannot trap large amounts of N before winter, >150 kg ha^{-1}, and early establishment may compromise weed control).**

- **Improve manure N use:**
  1. **Animal manures are generally more valuable to arable crops than to grass, except where the grassland is deficient in P or K (<index 2). Therefore, use manures to transfer N from the ley phase to the arable phase of the rotation.**
  2. **For best use of manure N make applications in spring at the start of rapid crop growth.**
  3. **The greatest yield response will be gained by spreading a small amount of manure over a large area.**
  4. **Uncomposted manures contain most available N and will give the greatest crop response.**

- **Matching crops with N availability:**
  1. **Legume residues usually release their N quickly after soil incorporation, so maximum use of legume N is ensured by minimising the time from incorporation to establishment of the next crop.**
  2. **Do not over-estimate N residues from grain legumes.**
  3. **Where N availability is expected to be small choose crops/cultivars with a small N requirement and a long period of N uptake, such as sugar beet and forage maize.**

SECTION 4: TECHNOLOGY TRANSFER OUTPUTS AND ACTIVITIES, AND FUTURE WORK

Transfer activities and outputs

- A poster was presented to the IFOAM 2000 Conference in Basle, in August 2000: *P M Berry, L Philipps & R Sylvester-Bradley*. 'An expert group approach to improving nitrogen use and performance of arable crops on organic farms in the UK'.
- Meetings were held with case study farmers and their advisors as part of the project.
- A presentation was made at meeting of the Society for Chemical Industry, Agriculture Group, in November 2001: *P M Berry, R Sylvester-Bradley, L Philipps, K A Smith, E I Lord, I Wright* and *W Cormack*. 'Tactical Management of nitrogen'.

  A presentation was also made to the Nutrients in Organic Agriculture Group
- Two articles were published in the Elm Farm Research Centre Bulletin.

  'Optimising N management on organic farming systems' – November 2001 Issue

  'Managing Nitrogen on organic farms' – July 2002 Issue
- A review paper has been published in Soil Use and Management, volume 18: *P M Berry, R Sylvester-Bradley, L Philipps, D J Hatch, S P Cuttle, F Raynes & P Gosling.* 'Is the productivity of organic farms restricted by the supply of available nitrogen?'.

  Another paper has been submitted to Soil Use and Management: *P M Berry, E A Stockdale, R Sylvester-Bradley, L Philipps, K A Smith, E I Lord, C A Watson, S Fortune.* 'N, P and K budgets for crop rotations on nine organic farms in the UK'.

Future work

- Given the dependence of organic crop production on legume fixation of N, and N release from soil sources, improved N availability would be assisted substantially by better knowledge of N release patterns during and after growth of different legume species.
- The value of nutrient budgeting has been well illustrated by this and allied projects, and there is scope to develop further guidelines to help growers and advisory bodies budget nutrients.
- There will be a need to validate the main recommendations devised by this project, especially that yields and quality of cash crops will be increased by increasing their N supplies.
- There is scope to study how early sowings of cereals can reduce seed costs and increase yields, and to study differences between cereal species in N scavenging capacity.
- N management in organic systems would also be helped by investigating whether (i) the small N concentrations of organically-grown crops, and (ii) a soil micro-flora that has not encountered pesticides, cause different patterns of N mineralization compared with conventional farm systems.

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