DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS
Research and Development

Final Project Report

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Project title	Understanding soil fertility in organically farmed soils
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Executive summary (maximum 2 sides A4)

Organic farming aims to create an economically and environmentally sustainable agriculture, with the emphasis placed on self-sustaining biological systems, rather than external inputs. Building soil fertility is central to this ethos. ‘Soil fertility’ can be considered as a measure of the soil’s ability to sustain satisfactory crop growth, both in the short- and longer-term, and it is determined by a set of interactions between the soil’s physical environment, chemical environment and biological activity. The aim of this project was, therefore, to provide a better scientific understanding of ‘soil fertility’ under organic farming. The project is in line with DEFRA’s policy objective of greater technical support to organic farming.

The approach used was to undertake a comprehensive literature review at the start of the project, to assess and synthesise what information was already available. Studies were then designed to address specific questions identified from the literature review.

The literature review was written during the first year of the project. In addition to submitting written copies to DEFRA, the chapters were posted on a project website: www.adas.co.uk/soilfertility.

The Review was based around key questions:

- What are the soil organic matter characteristics and the roles of different fractions of the soil organic matter?
- Do organically managed soils have higher levels of organic matter (SOM), with a resultant improvement in soil properties?
- Is the soil biology different in organically managed soils, in terms of size, biodiversity and activity?
- Do organically managed soils have a greater inherent capacity to supply plant nutrients?
- What are the nutrient pools and their sizes?
- What are the processes and rates of nutrient transfer in relation to nutrient demand?
- What are the environmental consequences of organic management?

The project also included a large amount of practical work. This necessarily covered a wide range of topics, which were examined in a series of separate studies:

- Soil microbiology: a series of measurements focusing on two sites, undertaken by University of Wales Bangor (UWB)
- Field campaigns in autumn 1999 and spring/summer 2000: separate field sampling campaigns focusing especially on nutrient pools, undertaken by HDRA, ADAS and IGER

- Incubation studies: a series of three separate experiments to look in more detail at N dynamics, managed by ADAS, with support from IGER and HDRA

From the literature review and the practical work, the following was concluded:

Organic matter is linked intrinsically to soil fertility, because it is important in maintaining good soil physical conditions (e.g. soil structure, aeration and water holding capacity), which contribute to soil fertility. Organic matter also contains most of the soil reserve of N and large proportions of other nutrients such as P and sulphur.

Field management data gathered from farmers showed, however, that organic matter returns are not necessarily larger in organic systems. Many non-organically farmed soils receive regular manure applications and the generally higher yielding crops on conventional farms may return larger crop residues. Conversely, many organic fields receive little or no manure, relying on the fertility building ley phase for organic matter input. This observation is important. Management practices within organic and non-organic systems are diverse and, sometimes, overlapping with consequences for soil fertility.

Soil Structure

Whilst addition of SOM generally promotes an increase in soil aggregate stability, only a part of the total SOM (generally the younger SOM with a larger content of polysaccharides, roots and fungal hyphae) stabilises aggregates: fungal hyphae (the biological agent) and extracellular polysaccharides (major cementing agents, deriving from plants and soil bacteria) are capable of linking together mineral particles and stabilising aggregates.

Thus, the most significant SOM components in agronomic systems are transient materials that exert their effect for one year at most. This correlates with the observation that aggregate stability is greatest under grass, where there is continuous production of these components, and decreases rapidly under arable cultivation.

This suggests that optimal aggregate stability requires the frequent turnover of transient organic matter residues, although humic substances also offer some long-term stabilisation of structure. Therefore, a ‘biologically active’ soil is better predisposed to better aggregate stability.

Our measurements generally showed better structure soon after ploughing the fertility building ley. On average, comparisons with conventional systems did not show organically farmed soils to be consistently better or worse in terms of structure.

Soil biology

The soil hosts complex interactions between vast numbers of organisms, with each functional group playing an important role in nutrient cycling: from the macrofauna (e.g. earthworms) responsible for initial incorporation and breakdown of litter through to the bacteria with specific roles in mobilising nutrients.

Earthworms have many direct and indirect effects on soil fertility, both in terms of their effects on soil physical properties (e.g. porosity) and nutrient cycling through their effects on micro-floral and -faunal populations (density, diversity, activity and community structure).

Thus, although microorganisms predominantly drive nutrient cycling, mesofauna, earthworms and other macrofauna play a key role in soil organic matter turnover. Factors that reduce their abundance, be it natural environmental factors (e.g. soil drying) or management factors (e.g. cultivation, biocides), will therefore also affect nutrient cycling rates. Organic farming’s reliance on soil nutrient supply requires the presence of an active meso- and macro-faunal population.

Our simple measurements showed more earthworms under the organic systems (compared with conventional) and generally more worms immediately after a ley compared with later in the rotation. We also found evidence of more beneficial nematodes in organic systems.

The soil microbial biomass (the living part of the soil organic matter excluding plant roots and fauna larger than amoeba) performs at least three critical functions in soil and the environment: acting as a labile source of carbon (C), nitrogen (N), phosphorus (P), and sulphur (S), an immediate sink of C, N, P and S and an agent of nutrient transformation and pesticide degradation. In addition, microorganisms form symbiotic associations with roots, act as biological agents against plant pathogens, contribute towards soil aggregation and participate in soil formation.

Critical evaluation of the significance of soil microbial biomass is hampered by its reliable measurement, and simultaneous partitioning of its three major functions in soil. For comparative purposes, soil microbial biomass and its derived indices have been successfully used to measure early changes induced by farming practices, and we adopted some of these methods. The relative importance of various environmental variables in governing the composition of microbial communities could be ranked in the order: soil type > time > specific farming operation (e.g., cover crop incorporation or sidedressing with mineral fertiliser) > management system > spatial variation in the field.

Generally, organic farming practices have been reported to have a positive effect on soil microbial numbers, processes and activities. Much of the cited literature has made direct comparisons between organic/biodynamic and non-organically managed soils. The evidence generally supports the view of greater microbial population size, diversity and activity, and benefits to other soil organisms too. However, little is currently known about the influence of changes in biomass size/activity/diversity on soil processes and rates of processes. Nor is it possible to conclude that all organic farming practices have beneficial effects and non-organic practices negative effects.

Our measurements, however, generally suggested differences in soil microbiology of soils managed under organic and conventional regimes were subtle rather than dramatic.

Nutrient cycling

Organic farming seeks to build up the reserves of nutrients in the soil while at the same time reducing inputs. This apparent conflict can only be resolved by increasing the efficiency of nutrient use and moving away from a definition of fertility based on the production of maximum yields. Because of the fertility-building and fertility-depleting stages of organic rotations, it is difficult to define the overall fertility of an organically farmed soil from measurements at a single stage of the rotation. It is also more important to include measurements of the reserves of less-readily available nutrients (e.g. organic P and non-exchangeable K) in assessing fertility than with non-organically farmed soils. Differences are more apparent with arable than with grassland soils because the latter usually have higher organic matter contents, irrespective of whether they are managed non-organically or organically.

Our measurements of a range of different nutrient pools reflecting short- and long-term supplies found no consistent differences for P and K within organic rotations, nor when compared with non-organically managed soils. We conclude that nutrient supply is governed by soil reserves that have developed as a result of previous managements and of current P and K inputs and offtakes. Nitrogen is, of course, more labile. In the absence of soluble fertilisers, N supply was also governed by history of inputs, particularly recent inputs of labile organic sources (leys, manures). There was an indication from incubation studies that some soils were better predisposed to mineralising the organic N, though effects were not consistent within or between farming systems. Further work is warranted on this aspect.

Thus, it can be concluded that although nutrient management in organically managed soils is fundamentally different to soils managed non-organically, the underlying processes supporting soil fertility are not. The same nutrient cycling processes operate in organically farmed soils as those that are farmed non-organically although their relative importance and rates may differ. Nutrient pools in organically farmed soils are also essentially the same as in non-organically managed soils but, in the absence of regular fertiliser inputs, nutrient reserves in less-available pools might, in some circumstances be of greater significance.

The information gathered during this project now needs to be provided in a usable form to growers and advisors. The project has gone some way to making the information available. However, we suggest that a booklet is produced, summarising the main findings and their implications for best management of organically farmed soils.

Scientific report (maximum 20 sides A4)

BACKGROUND

‘Soil fertility’ can be considered as a measure of the soil’s ability to sustain satisfactory crop growth, both in the short- and longer-term. Soil fertility is determined by a set of interactions between the soil’s physical environment, chemical environment and biological activity. Organic matter is linked intrinsically to soil fertility, because it is important in maintaining good soil physical conditions (e.g. soil structure, aeration and water holding capacity), which contribute to soil fertility. Organic matter also contains most of the soil reserve of nitrogen (N) and large proportions of other nutrients such as phosphorus (P) and sulphur (S).

Broadly speaking, organic farming aims to create an economically and environmentally sustainable agriculture, with the emphasis placed on self-sustaining biological systems, rather than external inputs. It is much more than simply replacing synthetic inputs with natural ones, though it is often described as such. This association of nutrient cycling with living organisms fits well with the organic ethos of sustaining soil fertility through the employment of natural processes rather than external inputs.

The organic standards, however, do recognise the need for, and permit the use of, some inorganic fertilisers within certain guidelines. Permitted substances are generally relatively insoluble products, which are made available to crops largely by the action of microorganisms, for instance rock phosphate (exceptions being the application of micronutrients and restricted use of soluble forms of K fertiliser).

However, the basic philosophy, within which all the Certification Bodies work, is one of building and maintaining inherent soil fertility, through the employment of natural biological processes, as opposed to importing short-term fertility in the form of soluble mineral fertilisers, as occurs in conventional farming.

We can hypothesise that soil fertility may differ between soils and systems because of several factors:

1. Different nutrient pool sizes (e.g. a smaller concentration of a dissolved nutrient in the soil solution, but a larger pool of labile - easily decomposable - organic compounds)
2. Different processes for nutrient transfer (e.g. solubilisation of rock phosphates, a much greater reliance on mineralisation of organic residues, or differences in food web composition)
3. Different rates of transfer of nutrients between pools (e.g. the ability to break down organic residues more quickly)
4. Different rates and degrees of retention within the system (for example, an observation in grassland soils is that whilst the biological processes leading to losses are speeded up by increasing levels of inputs, those responsible for internal transfer within the soil operate more efficiently)
5. Differences in other properties that influence root volume/depth, water holding capacity, etc. (and interactions responsible for the different activities in (2))

Whatever the factors, it is clear that soil biological processes play a major role in organically managed soils (Arden-Clarke & Hodges, 1988). With much of the evidence on soil fertility and crop performance in organic systems being anecdotal, there is a need for a better scientific understanding of the processes affecting nutrient availability and fertility. This enables development of advice for the better management of organically (and non-organically) managed soils. The potential for long-term depletion of soil fertility is one of the main criticisms of organic farming. It is often claimed, by its detractors, that organic farming is “mining” resources of P and K built up over the last forty to fifty years through the use of conventional fertilisers, and that it is ultimately not sustainable.

Although recognising the role of possible changes in physical attributes, this project focused primarily on the nutrient cycling aspect of soil fertility, which was considered to be an expression of all contributing factors whether biological, physical or chemical in nature.

The aim of the project was therefore to provide a better scientific understanding of ‘soil fertility’ under organic farming. The project is in line with DEFRA’s policy objective of greater technical support to organic farming. It provides information to support policy but, just as importantly, it provides practical information for organic farmers. It also contributes to the current debate on soil quality.

OBJECTIVES

Overall objective:
To provide a better understanding of nutrient cycling in organically managed soils, and to define the processes (including the role of biological diversity) involved and their controlling factors.

Detailed objectives:

1. To undertake a comprehensive review of the scientific literature on all aspects of soil fertility in organically managed soils.

2. To select appropriate measurement techniques for detailed nutrient cycling measurement.
3. To identify sites and select the most appropriate for detailed nutrient cycling measurement.
4. To conduct field, pot and laboratory studies, to compare the changes with time in fertility of soils under organic management in terms of
    - nutrient pool sizes
    - rates of transfer between nutrient pools
    - soil biological activity and processes influencing rates of transfer and nutrient availability
    - changes in form and function of soil organic matter and the residues returned to the soil
5. To conduct field, pot and laboratory studies, to measure the effects of key fertility building and fertility depleting stages in organic rotations in terms of
    - nutrient pool sizes
    - rates of transfer between nutrient pools
    - soil biological activity and processes influencing rates of transfer and nutrient availability
    - changes in form and function of soil organic matter and the residues returned to the soil
6. To assimilate and interpret the results of the review and of the practical studies to provide practical advice to both DEFRA and the organic farming community in terms of
    - factors affecting soil fertility
    - sources of nutrient supplies
    - measuring and optimising nutrient supply
    - providing the basis of field diagnosis of fertility
7. To identify the suitability of existing organic experiments for longer-term studies in this topic area.
8. To publish results from this project, and others, in a special edition of Soil Use and Management.

METHODS

The project was broad in its remit and necessitated a broad approach. A comprehensive literature review was therefore undertaken at the start of the project, to assess and synthesise the information that was already available. Studies were then designed to address specific questions identified from the literature review. The review also enabled us to assess the investigative techniques available for further soil fertility experimentation.

1. Literature review (Objective 1)

The literature review was written during the first year of the project and contained the following sections: Executive Summary; Summary; Conclusions and Recommendations; Introduction; Soil Management and Amendments; Soil Physical Effects; Soil Biology Effects; Nutrient Cycling Effects; Bibliography. In addition to submitting written copies to DEFRA, the chapters were posted on a project website: www.adas.co.uk/soilfertility. This allowed wide access to the Review. The site has been accessed over 2000 times (see Technology Transfer Section).

The Review was based around key questions:

- What are the soil organic matter characteristics and the roles of different fractions of the soil organic matter?
- Do organically managed soils have higher levels of organic matter, with a resultant improvement in soil properties?
- Is soil biology different in organically managed soils, in terms of size, biodiversity and activity?
- Do organically managed soils have a greater inherent capacity to supply nutrients?
- What are the nutrient pools and their sizes?
- What are the processes and rates of nutrient transfer in relation to nutrient demand?
- What are the environmental consequences of organic management?
- What are the implications of our findings for the better management of soils on organic farms?

The Results and Discussion of this report are similarly based around these questions, using the evidence from the literature review and the supporting practical work undertaken during the project.

2. Practical work

The project undertook a large amount of practical work. Full details are reported in the Appendices, with only brief, supporting information reported within this project summary. The project necessarily covered a wide range of topics, which were examined in a series of separate studies:

- Soil microbiology: a series of measurements focusing on two sites, undertaken by University of Wales Bangor (UWB)
- Field campaigns in autumn 1999 and spring/summer 2000: separate field sampling campaigns focusing especially on nutrient pools, undertaken by HDRA, ADAS and IGER
- Incubation studies: a series of three separate experiments to look in more detail at N dynamics, managed by ADAS, with support from IGER and HDRA

2a. Selection of methods and sites (Objectives 2 and 3)

The literature review allowed an assessment of methods commonly used in measurement of soil fertility. Many of these were used during the project, described later. Selection of sites was the more challenging aspect of the project. This was because of the shortage of long-term, replicated systems experiments in the UK, i.e. structured experiments that allow comparisons within a system and between systems (e.g. conventional vs organic). The DOC experiment (Alfoldi *et al.*, 1996) is a classic example of the benefit of such an investment: a long-term, replicated systems experiment that is now demonstrating subtle but potentially important differences in aspects of soil fertility that would otherwise be lost in the variability associated with less well-matched field and farm comparisons (Mader *et al.,* 2002).

In the absence of suitable systems experiments, we opted to structure many of the measurements by using a number of farms as replicates, and comparing different points within the rotation (end of fertility building versus end of fertility depleting), and by comparing with conventional equivalents when possible. Our basis for including conventional systems in the comparisons was not to determine if one system was ‘better’ or ‘worse’ (generally an invalid question – the systems are ‘different’), but to use the conventional systems as our baseline because generally more is known about these systems.

2b. Microbiological measurements and experiments (Objectives 4, 5 and 6)

Two farm sites, each maintaining both "conventional" and "organic" management regimes, were used in the study. In addition, soils from other sites (supplied by other groups involved in the overall project) were analysed as required. The major farm sites were: (i) Co-operative Wholesale Society (CWS) Stoughton, Leicester and (ii) ADAS Terrington, Norfolk. At CWS Stoughton, soils from a maximum of six fields were sampled, while at ADAS Terrington soils were taken from four fields (Table 1). The timings of soil sampling at CWS Stoughton and ADAS Terrington are shown in Table 1.

Table 1. Sampling times and cropping regimes at the sites used for soil microbiological analyses. ‘X’ indicates that no samples were collected from the site on that date.

(a) CWS Stoughton

Sampling	Rotation					
Date	Conventional	Integrated	Organic 1	Organic 2	Organic 3	In conversion
15/11/99	Winter wheat	Winter wheat	Clover ley	Winter oats	Winter oats	Clover ley
26/06/00	Winter wheat	Winter wheat	Clover ley	Winter oats	Winter oats	Clover ley
23/11/00	Stubble (Set aside)	Stubble (Set aside)	Clover ley	X	Clover ley	X
08/02/01	Stubble (Set aside)	Stubble (Set aside)	Clover ley	X	Clover ley	X
30/08/01	Stubble (Set aside)	Stubble (Set aside)	Clover ley	X	Clover ley	X

(b) ADAS Terrington

Sampling	Rotation			
Date	Organic 1	Organic 2	In conversion	Conventional
03/05/00	Spring beans	Winter wheat	Winter wheat	Winter beans
19/09/00	Stubble	Stubble	Stubble	Stubble
24/05/01	Spring barley /clover	Spring beans	Spring barley /clover[a]	Winter wheat
29/08/01	Clover	Stubble	Clover	Stubble

(a) denotes start of conversion

The soil sampling regime involved taking six samples (each of *ca*. 2 kg) from each field, at 10 m intervals in a 3 x 3-grid pattern. Sampling depth was *ca.* 5-20 cm. Soils were returned to Bangor in insulated containers, sieved (< 6.7mm) and stored at 4°C ahead of analytical work. Table 2 shows the measurements that were made.

Statistical Analyses

The majority of data were subjected to one-way Analysis of Variance (ANOVA). Where there were insufficient numbers of samples for ANOVA, data were analysed using unpaired t-tests. "Instat version 3 for windows" (GraphPad Software, USA) was utilised for both ANOVA and t-test analyses. Significance was calculated, using the Instate software, to 95%, 99% and 99.9% confidence limits.

Table 2. Summary of measurements made during the microbiological studies

Soil Physical and Chemical analyses	Microbiological analysis	Molecular biological techniques

• Soil moisture content
• Soil mechanical analysis
• Soil pH.
• Total organic C
• Potential organic C mineralisation
	• Indirect (plate) counts of soil microorganisms
	• Soil microbial biomass C
	• Soil microbial biomass N
	• Soil microbial biomass P
	• Determination of soil ATP
	  • *Readily extractable soil ATP.*
	  • *Total soil ATP.*
	• Basal- and substrate-induced respiration (SIR)
	• Soil microbial metabolic profiles: Biolog system
	• Total and vital fungal biomass
		• Enumeration of bacteria using 4’,6-diamidino-2-phenylindole (DAPI).
		• Enumeration of ribosome-rich bacteria (RRB)

2c. Field studies, autumn 1999 and spring/summer 2000 (Objectives 4, 5 and 6)

The field studies comprised of two separate campaigns: Autumn 1999 and Spring/summer 2000. Measurements in Autumn 1999 were single visits to a larger number of farms, as a ‘broad sweep’ to estimate the general soil fertility status. This was followed up by more detailed, sequential measurements through spring and summer 2000 on four farms. This allowed a more detailed assessment of aspects of soil fertility and the interaction with crop nutrient supply.

Autumn 1999

Sampling strategy

Soil samples were collected from 33 farms during winter 1999/2000. The majority were mixed farms but the sample also included stockless and predominantly grassland farms. Where possible, three fields were sampled at each location; representing an organically managed field at the high (H) and at the low (L) fertility stages of the rotation and a non-organically managed field (C). The high fertility stage of the rotation on the organic farms was considered to be the final year of the fertility-building ley phase or directly after ploughing the ley. The low fertility stage was at the end of the arable cropping phase or the start of a new ley. This distinction between high and low fertility soils was not applicable on the predominantly grassland farms and in these cases, a single grass field was sampled on the organic farms (categorised as high fertility). At each site, a single non-organically farmed soil was also collected, either from an unconverted field on the organic farm or from a field with the same soil series and topsoil texture on a nearby conventional farm (within 2 km of the organic fields).

All organically farmed fields had been certified as organic for at least 6 years. None of the selected fields had received inorganic fertiliser or animal manure in the 6 weeks prior to sampling. In total, samples were collected from 57 fields on mixed farms, 14 on stockless farms and 16 on grassland farms. In each of the stockless and grassland categories, there were two organically farmed fields for which there was no satisfactory conventional field to provide a comparison and these were excluded from the statistical analysis of the data.

Sampling method

Within each field, a representative area of 50 m x 25 m was selected for study. Soil samples for chemical analysis were collected at random from this area (n=20) using an auger to 20 cm depth in the ley and arable fields on the mixed and stockless farms and to 7.5 cm for fields on the predominantly grassland farms. Soils were air-dried and passed through a 2 mm sieve prior to storage and subsequent chemical analysis. At the same time as collecting soil samples, a field assessment was made of soil structure for 0 - 7 cm and 8 - 20 cm soil depths at 10 random points within the sampling area. Structure was assessed on a scale of 1 (poor) to 10 (good) (MAFF, 1985). Numbers of worms in the 0 - 7 cm depth were visually assessed on a scale of 1 (none) to 3 (frequent). Dry bulk density was also determined on soil samples (1.5 - 6.5 and 12.5 - 17.5 cm depths) collected at three random points. Cropping and management data as reported by the farmer were also recorded for each sampling site, together with data for previous years back to 1995, where available. A hand assessment of soil texture was also made.

Analytical methods

Table 3 summarises the analyses undertaken on each soil.

Statistical analysis

Comparisons between the properties of soils at different stages of the organic rotation and between organic and non-organically farmed soils were conducted using paired t-test (two-tailed) and also by analysis of variance with management as treatments and the site as replicates (blocks). Differences between worm count scores were analysed by the Wilcoxon Matched-Pairs test because the data were not normally distributed. Correlation between the different properties was also examined. Because of the different sampling depth, soil properties for the grassland farms were in most cases analysed separately from those for the mixed and stockless farms.

Table 3. Chemical analyses undertaken on soils in the laboratory

Determinand	Reference
Soil pH (water)	MAFF, 1986
Organic C	
Organic N	
Potentially mineralisable N by anaerobic incubation (PNM)	Lober & Reeder, 1993
Total S	
Extractable S	MAFF, 1986
Water-soluble P	
Olsen-P (sodium bicarbonate extract)	MAFF, 1986
16-h Olsen P (modified to include extractable organic P)	Tiessen *et al.,* 1984 Cross & Schlissinger, 1995
Total P	
Exchangeable K (ammonium nitrate extract)	MAFF, 1986
K extracted with boiling nitric acid	Knudsen *et al*., 1982
Exchangeable Mg (ammonium nitrate extract)	MAFF, 1986

Spring/summer 2000

Site selection

Four farm sites were sampled during the spring and summer of 2000. They were a stockless arable farm on silty clay loam (Agney series) in Norfolk (Farm N), a mixed dairy farm on clay (Evesham series) in Oxfordshire (Farm O), a mixed farm on fine loam over clay (Oxpasture series) in Warwickshire (Farm W) and a mixed dairy/stockless arable combination on silt loam/sandy silt loam over limestone rubble (Elmton series) in Gloucestershire (Farm G). The farms chosen represented well-run, large enterprises and thus should have provided a good indication of soil fertility in organic mixed/arable systems.

At each site, three fields were selected: one organic field in a first cereal after ley (‘High Fertility’), one organic field in a final cereal before being returned to ley (‘Low Fertility’) and a third field in cereal under non-organic management (‘Conventional’). Except in the case of Farm G, the organically and non-organically managed fields were on the same farm. This site selection strategy was adopted to minimise differences in soil texture between fields on each farm. At Farm G, the conventional field and the organic fields were on different farms but were adjacent. All organic fields had been converted for at least 6 years and in the case of Farms O, G, and W for longer. All first cereals were winter wheat, as were all conventional crops, but final cereals in the organic systems were triticale on Farm O, spring barley on Farm N, winter oats on Farm W and winter wheat on Farm G, although complicating the picture to some degree, this was unavoidable due to the nature of organic rotations.

Soil and crop sampling

All farms were sampled initially in April or early May with final sampling after harvest in September or early October. Table 4 shows the sampling routine used. In each field, a representative area approximately 25 x 50 m was selected at the start of the sampling period, and all samples were taken from within this area. Soil was sampled with augers to a depth of 90 cm, except at Farm G where it was sampled to the maximum soil depth (40-60 cm); samples were split into 0-30, 30-60 and 60-90 cm sub-samples. Ten sub-samples were bulked to make a sample and three samples were taken per field per visit, collected in the standard ‘W’ pattern. Samples of total above ground crop and weed biomass were taken from three randomly placed, 50 x 50 cm quadrats per field per visit.

During the first and last sampling visit, an assessment was made of soil structure and a crude assessment of biological activity was made. Soil structure was assessed visually using an objective technique at ten positions in each field (MAFF, 1985). Twenty bulk density measurements were also made at random locations in each field using bulk density tins, 10 at 0-8 cm and 10 at 8-20 cm depths. Soil biological activity was estimated from both earthworm numbers and from measurements of soil respiration. Earthworm numbers were estimated from three 50 x 50 x 50 cm pits dug at random positions in the sampling area, except at Farm G where the pits were only 40 cm deep due to limited soil depth. The soil was sifted by hand and the number of earthworms noted. Soil respiration was estimated by measuring carbon dioxide evolution using a portable infra-red gas analyser at 20 random positions in each field.

During the sampling period, assessments were also made of field N mineralisation rates using the Kilner jar technique (Hatch *et al*., 1990, 1991). Three soil cores were taken and divided into 0-15 cm and 15-30 cm depths. The cores were then placed into Kilner jars with minimal disturbance and buried at the depth from which they were removed. Four pairs of jars were used per field. Soil samples were taken at the same time for analysis of initial mineral N concentration. The jars were recovered after two weeks and the soil analysed for mineral N. Because they were only being left for 2 weeks the jars were not sealed (thus avoiding oxygen depletion) and no acetylene was used as it was felt there would be little if any denitrification. Four incubations were carried out at each site. Data were collected from farmers detailing the management of individual fields for the previous five years to aid interpretation of the data.

Contents of exchangeable-K, Olsen-P and calcium chloride-extractable P and K were measured in the fresh (non-air dried) soils. In addition, soils from the first sampling were also extracted for free and protected light fraction organic matter (LFOM), plus analysis for C and N content. Anaerobic incubations were also undertaken on these soils as a further assessment of labile organic N content, using an adaptation of the method of Lober & Reeder (1993).

Table 4. Sampling schedule for crops and soils.

	Monthly	Start and end
Soils for N, P and K	X	
Crop dry matter	X	
Weed dry matter	X	
Soil respiration		X
Worm counts		X
Bulk density		X
Visual structural assessment		X
In situ N mineralisation	X	

Statistical analysis

Statistical analysis was by analysis of variance using farms as blocks, or by non-parametric methods where analysis of variance was not appropriate

2d. Incubation and nitrogen studies (Objectives 4, 5 and 6)

To supplement, and build upon, the findings of the field measurements and the microbiological studies, a series of more detailed laboratory incubation studies were undertaken. These used soils from different sources as outlined below, and used aerobic incubations with and without added crop residue to learn more about the N cycling capability of the soils.

The soils were incubated at 20 ^{o}C at 60% of their water holding capacity, with or without an added crop residue of dried and finely ground clover. The soils were sampled at intervals to measure the accumulation of mineral N derived from mineralisation of native organic matter and the added crop residue. The clover had a N content of 3.9% and a C:N ratio of 9. Each incubation vessel contained 50 g of moist soil, to which was added 0.3 g of residue. This provided a total N loading of *c.* 250 mg/kg dry soil.

Study 1

The objective was to test the hypothesis that organically farmed soils are more rapidly able to mineralise organic materials compared with their non-organically farmed equivalents. Pairs of soils (organic v non-organically farmed) were collected from three farm sites. Additionally, a fourth, non-organically farmed soil with and without regular FYM additions was included. Each soil was aerobically incubated for 10 weeks at 20 ^{O}C under controlled conditions with and without an added crop residue to monitor changes in soil mineral N status, as described above. The University of Wales, Bangor, undertook supporting measurements of soil microbial properties at the start of the experiment.

Study 2

The objective was to test the hypotheses that organically managed soils receiving regular applications of organic amendments:

- are able to mineralise organic materials more rapidly than their non-organically farmed equivalents
- have a more active biomass
- have a larger light organic matter component

The Study utilised an existing medium-term replicated experiment at the organic field site at HDRA. The experiment had previously tested the effects of repeated manure and compost applications on soil properties. Treatments had been applied annually for 6 years:

1. Control (no amendment applications)
2. Green waste compost – low rate
3. Green waste compost – medium rate (2 x low rate)
4. Green waste compost – high rate (3 x low rate)
5. Cattle FYM
6. Poultry manure
7. Cattle slurry

Apart from treatments 2 and 3, the manures had been applied at a rate to supply 250 kg N/ha. Approximately 2.5 kg of soil from each plot, 0-20 cm, was taken using a cheese corer auger and following a 'W' pattern across each plot (i.e. 28 samples). Each sample was thoroughly mixed and split into two: approx. 500 g was sent to UWB, keeping the soils cool and ensuring rapid dispatch; approx. 2 kg was sent to ADAS Gleadthorpe (again, keeping the soils cool and ensuring rapid dispatch). The following measurements were made on the soils:

Field capacity moisture value; soil total N and C; Potential Nitrogen Mineralisation (PNM) by anaerobic incubation; microbiological measurements; LFOM content and C and N analysis of the light fraction; aerobic incubation with and without an added crop residue (12 weeks, method as described above).

Study 3

A third study was completed using soils from 6 farms and three fields per farm: non-organically farmed, high fertility organic (end of fertility building stage) and 'low fertility' organic (end of fertility building stage). The objective of this work was to test whether these soils differed in their ability to mineralise an added crop residue measured over 4 weeks. Only well-established organic sites (>10 years) were used in this Study. The aerobic incubation procedure, as described above, was used.

3. Journal publication

After the project was started, it was agreed with DEFRA that a useful way of disseminating results would be to summarise findings from this project and others in a peer reviewed journal. Additional funding was therefore sought to publish a special edition of Soil Use and Management: 'soil fertility in organically farmed soils – fundamentally different?'. The papers have been completed and publication is due in summer/autumn 2002.

RESULTS AND DISCUSSION

1. Do organically managed soils have higher levels of organic matter, with a resultant improvement in soil properties?

Literature review

The scientific literature clearly demonstrated the benefit of increasing levels of organic matter on all aspects of soil fertility. Whether organically farmed soils generally have larger soil organic matter contents than non-organically managed soils depends on the size of the C inputs (as residues, manures, etc.) over the whole rotation. Consequently, few differences in organic matter content have been reported between organic and non-organically managed pasture soils because these tend to have similar inputs of organic matter. In studies comparing non-organically and organically managed arable soils, the organically managed ones have tended to have higher organic matter contents because of the greater use of manures in these rotations.

Because of the greater reliance of organic returns in organic systems, it is possible that organic matter levels will be greater in these soils. However, it does depend very much on the C balance of individual systems. Differences are therefore likely to be least in pasture systems, and the few examples of arable experiments with similar manure inputs on both the non-organic and organic treatments have also shown no differences in organic matter content. High yielding crops (more likely in non-organic systems) also return more crop residue. Therefore, it is not certain that these benefits are exclusive to organically farmed soils.

Measurements

Measurements of soil organic matter in the field experiments confirmed that there was rarely a consistent difference in soil total organic matter content between the non-organic and organically farmed soils that we sampled: see Table 5 (1999 and 2000 data). Inspection of the field histories for these samples showed a wide range of organic inputs (crop residues, manures), such that it was not surprising that consistent differences in organic matter were not found.

Table 5. Soil organic matter content of fields measured during autumn 1999 and spring/summer 2000 (means and standard errors). There were no significant (P<0.05) differences between rotational position with either set of samples

		Organic high fertility	Organic low fertility	Non-organic
Field campaign 1 - Autumn 1999				
Organic C	(%)	2.5 (0.18)	2.3 (0.16)	2.4 (0.18)
Total N	(%)	0.31 (0.02)	0.29 (0.02)	0.29 (0.03)
Field campaign 2 - Spring 2000				
Organic C	(%)	3.9 (0.21)	3.5 (0.24)	3.8 (0.31)
Total N	(%)	0.29 (0.02)	0.24 (0.02)	0.26 (0.02)

This effect of C inputs on soil organic matter was shown when soils from HDRA were sampled (Incubation experiment 2). The results clearly showed differences between treatments (Table 6) and these differences could be related to the different C inputs in previous years.

Table 6. Soil carbon and nitrogen contents from soils sampled at HDRA (Incubation experiment 2).

Treatment	Total C (%)	Total N (%)	C:N ratio
Zero	2.15	0.21	10.4
Compost - low rate	2.40	0.23	10.6
Compost - medium rate	2.70	0.25	10.9
Compost - high rate	2.87	0.27	10.8
Cattle FYM	2.43	0.23	10.6
Poultry manure	2.31	0.22	10.4
Cattle slurry	2.30	0.27	9.2
P value	0.001	0.35	0.43
standard error	0.095	0.022	0.55

Table 7. Structural scores and dry bulk densities of soils from different management: mean (standard error). Within a row, means followed by the same letter are significantly different at P<0.05 when comparing organic (high fertility), organic (low fertility) and non-organic fields. In the final column ('all soils'), means followed by the same letter are significantly different at P<0.05. Data from autumn 1999 (Field campaign 1).

	Organic (high fertility)	Organic (low fertility)	Non-organic	All soils
Structural score: 0-7 cm				
Mixed	6.7 (0.21)	6.6 (0.18)	6.6 (0.16)	6.7 (0.11)
Stockless	7.2 (0.30) a	7.5 (0.18) b	5.9 (0.11) ab	6.9 (0.23)
Grassland	7.2 (0.30)		6.7 (0.19)	7.0 (0.19)
Structural score: 8-20 cm				
Mixed	5.9 (0.21)	6.0 (0.22)	5.8 (0.21)	5.9 (0.12)
Stockless	6.4 (0.44)	6.6 (0.28) c	5.4 (0.21) c	6.1 (0.23)
Grassland	6.4 (0.25)		6.0 (0.44)	6.2 (0.25)
Bulk density: 0-7 cm (g/cm^3)				
Mixed	1.01 (0.04)	1.02 (0.04)	0.99 (0.04)	1.00 (0.02) x
Stockless	1.07 (0.07)	1.08 (0.07)	1.20 (0.06)	1.12 (0.04) x
Grassland	0.81 (0.04) d		0.94 (0.06) d	0.88 (0.04) x
Bulk density: 8-20 cm (g/cm^3)				
Mixed	1.08 (0.04)	1.07 (0.03)	1.03 (0.05)	1.06 (0.02)
Stockless	1.14 (0.08)	1.05 (0.07)	1.20 (0.08)	1.13 (0.08)
Grassland	1.06 (0.09)		1.04 (0.14)	1.05 (0.04)

Organic matter plays an important role in soil structural development, particularly fresh additions (Shepherd *et al.*, 2002). Consequently, soil structure might be expected to be better under organic farming systems – and also better immediately after ploughing a ley compared with later in the rotation. Our 1999 dataset showed differences in soil structure score for the stockless and pasture soils (significant at P=0.08) but, on average, there was no difference for the mixed farms (Table 7). On these, however, some of the 'high fertility' fields were still in ley when assessed and it was noticeable that structure was much better in the ploughed leys compared with those waiting to be ploughed (structure scores 6.9 and 6.1, respectively).

The aim of Field Campaign 2 (spring/summer 2000) was to follow fewer fields than in 1999, but focus more on nutrient dynamics through the season. However, data from these 12 fields from mixed organic farms (Table 8) similarly confirm previous findings: sometimes better soil structure, sometimes not.

Table 8. Soil structural scores and dry soil bulk density as a mean of four farms measured during 2000 (Field campaign 2).

	Organic (high fertility)	Organic (low fertility)	Non-organic	*P* value
Structural score: 0-7 cm				
Spring	7.8 (0.06)	7.2 (0.12)	6.4 (0.12)	0.004
Autumn	6.7 (0.12)	6.0 (0.12)	5.7 (0.17)	0.34
Structural score: 8-20 cm				
Spring	6.7 (0.10)	6.0 (0.18)	5.7 (0.18)	0.007
Autumn	7.3 (0.11)	5.9 (0.14)	5.0 (0.25)	0.07
Bulk density: 0-7 cm (g/cm^3)				
Spring	1.18 (0.022)	1.20 (0.024)	1.15 (0.023)	0.59
Autumn	1.04 (0.024)	1.15 (0.017)	1.20 (0.025)	0.86
Bulk density: 8-20 cm (g/cm^3)				
Spring	1.13 (0.023)	1.21 (0.022)	1.22 (0.033)	0.34
Autumn	1.04 (0.023)	1.21 (0.020)	1.27 (0.028)	0.003

2. What are the organic matter characteristics and the roles of different fractions of the organic matter?

Literature review

Soil organic matter is a complex, heterogeneous material, composed of a continuum of organic material, stabilised to varying degrees by molecular recalcitrance, physical separation from the microbial biomass and/or direct association with inorganic ions and clay surfaces. In all soils (i.e. non-organically and organically managed) the following fractions of soil organic matter (SOM) can be identified:

- ***organo-mineral*** - i.e. SOM associated with the soil's silt and clay fractions, and this can constitute as much as 80% of SOM
- ***intra-aggregate*** - i.e. SOM associated with micro- or macro-aggregates
- ***free macro-organic matter***
- ***biomass***
- ***dissolved organic compounds***

These groups of constituents or 'pools' differ in composition and differ in the roles that they play in soil. The 'stable' organic matter (humus) is completely amorphous and is intimately combined with the mineral portion of the soil. It is colloidal in character and has properties of moisture and cation absorption (more than clay). The 'effective' humus is the fresh or young organic matter and, when combined with the microbial biomass, is now perhaps better known as the 'light fraction' of organic matter. It is this particularly active fraction that is involved in the SOM transformations that take place and so impacts on:

- nutrient supply (mineralisation/immobilisation)
- biological activity (a food source)
- physical stability

Although more stable humic substances also play a role in the long-term stabilisation of soil, by-products from decomposition of fresh residues, and fungal hyphae feeding on the residues, are important agents in soil stability.

Organic matter (carbon) is central to all farming systems, with additions in manures, catch/cover crops, leys, crop residues and rhizodeposition. High yielding crops return more C than lower yielding crops of the same species: well-fertilised crops will have an advantage in this respect over crops grown under conditions of sub-optimal nutrition.

The literature is conclusive on the benefits to soil fertility of organic matter. Differences in the proportions of nitrogen (N) associated with separate fractions of the organic matter (organo-mineral, intra-aggregate, free macro-organic matter and biomass) in soils from organic and non-organic farms reflect differences in the nature of the inputs to the soil. These differences are best characterised by analysis of the light fraction of the SOM (free macro-organic matter plus biomass). This light fraction responds more quickly to changes in management practices and so is a better indicator of change than is total organic matter measurement; future research should focus on this. It may be that dissolved organic compounds also play an important role in organic farming systems, but little is known of these, as yet.

Measurements

In addition to measuring total soil organic matter and N content, we chose to estimate the 'biologically active' component of soils in two ways:

- Measurement of LFOM in two studies (Field campaign summer 2000 and Incubation experiment 2)
- Measurement of mineral N release by anaerobic incubation in several studies.

Additionally, we measured dissolved organic N in soils through the spring/summer of 2000.

PNM measurements (anaerobic incubation) on soils collected during Field campaign 1 (autumn 1999), based on all 26 farms, showed a significant difference in readily mineralisable OM contents between organically farmed soils, at the end of the fertility-building phase (i.e. high fertility) and those at the start of a new rotation (i.e. low fertility), following an arable cropping phase (Table 9). Non-organically farmed soils were intermediate between the contrasting organic soils. When the N release was expressed as a proportion of the total soil N (viz. %N turnover), the relationships were the same, which suggests that the '*quality'* and not simply the *amount* of organic matter was the determining factor. This relationship held true when the data was blocked for mixed farming systems only, but although trends were similar, the numbers of all-grass and stockless systems was insufficient to show statistical differences.

Table 9. Measurements of 'labile organic N' by release of mineral N by anaerobic incubation over 7 days and by assessment of light fraction organic matter (LFOM) content.

		Organic high fertility	Organic low fertility	Non-organic	*P* value
Field campaign 1 Autumn 1999					
Anaerobic Inc	(mg N/kg soil)	97 (7.8)	72 (5.0)	78 (13.2)	0.07
Field campaign 2 Spring 2000					
Anaerobic Inc	(mg N/kg soil)	115 (17.8)	99 (21.2)	82 (17.0)	0.04
LFOM	(g/100 g soil)	0.49 (0.033)	0.41 (0.037)	0.45 (0.034)	0.36

In all four of the farms selected for more detailed study in 2000, PNM in the high fertility organic phase was at least 20% higher than in the non-organic soils ($P<0.05$). The soils in the low fertility phase tended to be intermediate. Rates of N turnover (PNM, expressed as a % of total soil N) ranged from 2 and 8%; maximum values were found in the organic soils of all four farms. On two of the four farms, rates were lower under non-organic management ($P<0.05$). Soluble (hot water) organic C was similar in soils from three farms; none of the fertilised soils exceeded values obtained in the organic soils in any of these farms. The LFOM was on average, 10% (by mass) of the total SOM and there were no differences between organic and non-organically managed soils. The C:N ratio of LF was similar in three farms (av. 18.2), the exception was the fourth farm where the LF in the non-organic soil had a higher C:N ratio ($P<0.05$). Overall, the proportion of N held in the LF represented only about half of that released by PNM.

Measurements of LFOM taken in summer 2000 were inconclusive, even though the sampling regime appeared to be adequately structured, using four farms and three rotational positions (Table 9). It may have been that the variability between soils was such that the method was unable to detect subtle differences. However, that such differences existed were confirmed by the anaerobic incubations, which detected differences in release of N from the organic matter as affected by rotational position.

Measurements taken from the HDRA experiment (Incubation experiment 2) showed that LFOM was related to organic matter inputs (Table 10 and Fig. 1). The manure/compost applications increased free (inter), protected (intra) and total light fraction organic matter, with effects being largest for compost and FYM. Results also showed that the proportion of organic matter present as LFOM increased, particularly with FYM and compost applications. Effects were especially large for the higher compost rates. Figure 1 confirms the linear relationships between annual N loading and total organic matter or LFOM contents for the compost applications (the only organic material where rate was included as a treatment). The slopes of the respective lines also show that total organic matter content increased at a rate greater than the LFOM content, but the percentage increase above the unamended control was greater for the LFOM than for SOM content.

The dissolved organic N pool might be expected to be larger under organic systems because, potentially, there might be more labile organic N in the system. Alternatively, if soil mineral N levels are less in organic systems, then dissolved organic N might represent an important N pool, even if there are no differences in absolute amounts between systems or within organic rotations. The limited number of measurements that were taken during spring/summer 2000, however, found no significant differences between absolute amounts (summarised in Fig. 2), although the content of Dissolved organic N (DON) relative to that of mineral N was greater in the low fertility situation. Further, more detailed work is required on this aspect.

Table 10. Light fraction organic matter content and CN composition (Incubation experiment 2)

Treatment	free (%)	protected (%)	total (%)	Total, as % of soil OM	Tot C (%)	Tot N (%)	C:N ratio
Zero	0.28	0.02	0.30	8.1	31.5	1.06	29.8
Compost - low rate	0.51	0.06	0.57	13.6	27.5	1.06	26.4
Compost - medium rate	0.70	0.07	0.76	16.4	27.3	1.22	22.4
Compost - high rate	0.93	0.13	1.06	21.2	30.9	1.24	25.0
Cattle FYM	0.48	0.05	0.54	12.7	27.6	1.10	25.1
Poultry manure	0.34	0.03	0.37	9.2	26.6	0.94	28.4
Cattle slurry	0.32	0.04	0.36	9.2	31.6	0.90	35.6
P value	<0.001	0.003	0.001	<0.001	0.10	0.005	<0.001
standard error	0.044	0.015	0.058	1.16	1.53	0.060	1.55

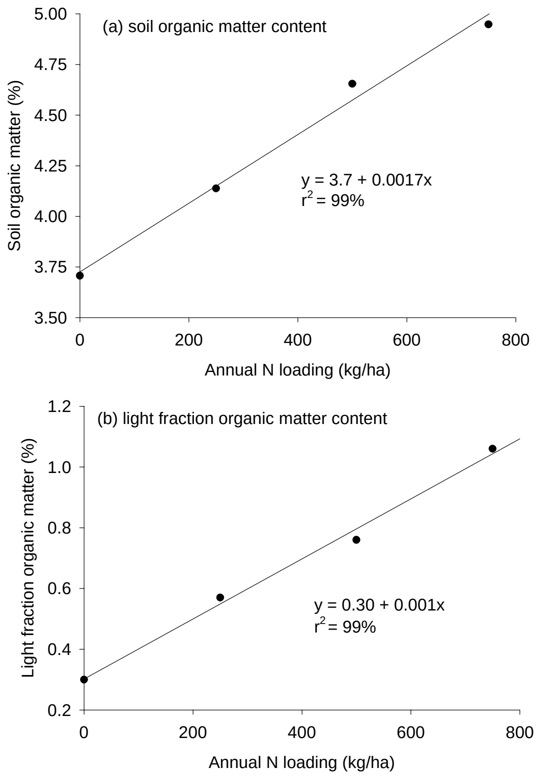


Figure 1. Effect of compost application rate on soil organic matter and light fraction organic matter contents (Incubation experiment 2)

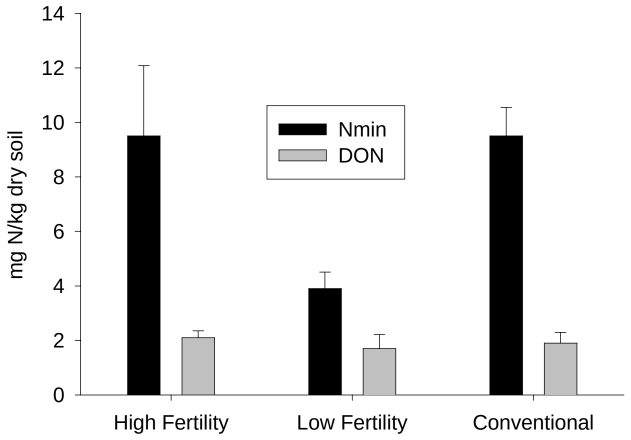


Figure 2. Average topsoil (0-30 cm) N contents through the spring and summer of 2000, as an average of four fields in each of the three rotational positions (Field campaign 2). Mineral N (Nmin) and dissolved organic N (DON).

3. Is the soil biology different in organically managed soils, in terms of size, biodiversity and activity?

Literature review

Soil organisms are central to nutrient cycling. Recent estimates that a single soil sample of a few hundred grams contains as many as 4,600 bacterial species (as well as many millions of individual microorganisms) emphasises further that soils are major reservoirs of microbial diversity. Life forms in soils may be divided into:

- microflora: bacteria, fungi, actinomycetes and microalgae;

- microfauna: organisms generally less than 100 um in length, feeding upon other micro-organisms, including single-celled protozoa, some smaller flatworms, nematodes, rotifers and tardigrades;
- mesofauna: larger organisms, including creatures that feed on micro-organisms, decaying matter and living plants - nematodes, mites, springtails, proturans and pauropods;
- macrofauna: slugs, snails and millipedes (feeding on plants), beetles and their larvae, fly larvae (feeding on other organisms or on decaying matter) and, most importantly, earthworms.
- megafauna: the largest soil organisms including vertebrates, such as moles.

Within this catalogue of life in the soil, it is the microbial biomass that is the powerhouse of nutrient cycling. However, food webs are extremely complex, with organisms from earthworms (initial incorporation and breakdown of residues) through to bacteria (specific roles in mobilising nutrients) involved in nutrient transformations. This complexity results in a diverse population of soil organisms involved in rapid nutrient turnover. The need for diversity has been called into question by the theory of ‘functional redundancy’ which infers that a loss of species will not necessarily be reflected by a change in rates of biologically mediated soil processes. However, functionally similar organisms often have different environmental tolerances, physiological requirements and microhabitat preferences, so that they are likely to play quite different roles in the soil system. It would seem sensible to maintain as diverse a population as possible, so as to enhance nutrient cycling in organic systems. An additional advantage of maintaining soil biodiversity is the potential for protection against plant damaging organisms. Soil fauna are recognised as potential suppressants of root pathogens. Some species of fungivorous amoeba, nematodes and springtails can selectively feed on phytopathogenic fungi.

These are the perceived advantages of a highly biodiverse population, so do organically managed soils differ from non-organically managed soils? First, it should be noted that soils are naturally variable in terms of biomass size, activity and composition: there is variation both within fields and between fields that have apparently been treated similarly. It is against this great variability that we have to make judgements about the effects of different farming systems.

While there have been a number of reports that have indicated that organic farming practices have positive effects on soil microbial numbers, processes and activities, other research data have suggested zero impact or even negative effects. It is not, therefore, possible to conclude that all organic farming practices have beneficial effects and all non-organic (non-organic) practices have negative effects. In the few arable comparisons where lack of differences, or greater activity in non-organic systems, have been found, this might be related to greater residue returns in the non-organically fertilised systems. If so, this provides a pointer that where differences do occur, the key factor that differentiates between non-organic and organic systems is the return of organic matter. The literature that shows no benefit of an organic system to microbial activity has often involved pasture systems. Differences are least likely to be apparent in this type of system, since both organic and non-organic pastures will accumulate organic matter. In addition, pesticide applications may, by inhibiting or killing components of the soil microbial community, promote changes in population biodiversity and dynamics. For example, fungicide application can cause significant changes to the relative sizes of the fungal and bacterial communities in soils.

There is evidence for the beneficial effect of organic farming on other organisms. For example, low populations of earthworms have been linked to lack of adequate moisture in the soil surface, intensive pesticide use, frequent tillage, and absence of ground cover. Organic management practices try to minimise these effects and are therefore more likely to encourage active earthworm (and, presumably, other soil macro-arthropod) populations. The literature tends to support this expectation. However, some cropping/cultivation practices have detrimental effects on earthworm numbers irrespective of whether grown organically or non-organically (e.g. potatoes).

There have been some suggestions that water-soluble fertilisers are harmful to the soil microbial biomass through their salt effects (by inducing osmotic stress etc.). For example, sulphate of potash (K_2SO_4) is considered significantly less toxic than muriate of potash (KCl), though the latter is the most common potassium (K) fertiliser used in non-organic agriculture and which supposedly can have serious detrimental effects on soil micro-organisms. However, the literature does not implicate salt effects and we suggest that evidence for this is generally scant and/or anecdotal.

Measurements

In summary, the data from both Stoughton Lodge and ADAS Terrington farms showed that total organic carbon (C) in soils managed under organic and non-organic regimes were mostly not significantly different from each other. This might be somewhat surprising in view of the greater reliance in organic farming on organic matter, which may be added either within a crop rotation (e.g. a clover ley), addition of composts, and/or by application of green or animal manures. This apparent anomaly may, however, be explained by consideration of the various ways in which organic materials enter soil ecosystems. In non-organically managed farmland, where fertilisers are applied as inorganic chemicals rather than as organic manures etc., organic matter inputs still occur. These organic sources include dead root matter (even where surface crop debris is removed rather than incorporated into the soil) and that which derives from growing plants. Significant amounts (estimated 3-15% of root dry weight) of organic materials enter soils as lysates, exudates etc. from active root systems (Newman, 1988). Jenkinson *et al.* (1992) estimated that the total net primary production in a continuous wheat plot at Broadbalk (Rothamsted, south-eastern England) receiving NPK fertiliser was 5.2 t C/ha/yr (with 1.7 t C/ha/yr being added to the soil), compared with respective figures of 2.2 and 1.3 t C/ha/yr in an unmanured plot.

Much of this was as small molecular weight compounds and mucilage. Crop yields are often lower in organic systems than in a more intensively managed non-organic regimes. This will result in lesser amounts of root exudates and root debris entering soils under organic management, which may not be compensated (in terms of C budgets) by the additional organic matter entering as added manure (typically about 1 t C/ha/yr averaged over several years in an organic system). In addition, although root lysates and exudates are metabolised by soil microorganisms, soil macro- and mesofauna (earthworms etc.) feed mostly on plant and animal debris, so that biological life in soils may be differentially impacted by organic versus non-organic management.

Differences in microbiology of soils managed under organic and non-organic regimes were found to be subtle rather than dramatic. Many of the techniques used in the present study failed to find consistent significant differences in microbial parameters in soils from either Stoughton Lodge or ADAS Terrington. This list includes the fumigation-extraction technique (which measures the size of the soil microbial C pool) and differential plate counts (which were used to evaluate the gross compositions of soil microbial populations). However, the ATP concentrations in Ringers solution extracts of Stoughton Lodge soils were mostly found to be significantly greater in organically than in non-organically managed soils. This might reflect either greater numbers of microorganisms in extracts of the "organic" soils, or indicate that the microorganisms present were more metabolically active (and therefore contained more ATP/unit cell) than their counterparts in non-organically managed soils. Results from a fluorescent *in situ* hybridisation (FISH) analysis using the EUB338-labelled probe showed that, although plate counts of prokaryotes were similar in all soils at Stoughton Lodge farm, total bacterial numbers were greatest in the stockless organic soils, which also contained the most readily-extractable ATP. These results suggest that the trends in readily extractable ATP were due to larger numbers of viable but non-culturable microorganisms in soils under organic management rather than those in non-organic systems. Evidence in support of this hypothesis came from microscopic measurements of total and vital fungal biovolumes; these were also found to be greater in the integrated than the non-organic field at Stoughton Lodge.

In contrast to the results obtained with soils from Stoughton Lodge farm, significantly greater concentrations of readily-extractable ATP were only found on one of three occasions in organically-managed plots in soils from ADAS Terrington. However, analysis of soils from three other farms in which organic and non-organic systems were running in parallel produced similar results to those found at Stoughton Lodge rather than those seen with ADAS Terrington soils. These data showed no significant difference in net biomass C (determined by fumigation-extraction) but significantly greater readily-extractable ATP in the organically-managed than the non-organically-managed soils (or those receiving bulk manure compared with those receiving only inorganic NPK, in the case of soils from ADAS Gleadthorpe). The only soils in this experiment that did not contain more readily extractable ATP in organic plots were again those from ADAS Terrington, though soils from this farm were unique in containing significantly more biomass C in the high fertility organic plots than those under non-organic management. The general conclusion was therefore that the method developed and used widely in this project to assess "readily extractable" soil ATP is a technique which, unlike many others used in soil microbiological studies, can and does reveal differences between soils under organic and non-organic management.

The finding that organic management may result in soils having greater proportions of viable but non-culturable soil microorganisms has implications for diversity of indigenous soil microflora. Preliminary measurements on the nutritional biodiversity of the microorganisms in these soils, using the Biolog^{TM} system, failed to find differences between organically- and non-organically-managed soils, though more extensive use of this technique is required before firm conclusions can be drawn.

Table 11. Field campaign 2, 2000. Worm counts (number per 50 cm x 50 cm x 50 cm pit) and non-plant pest nematodes (number per litre of soil)

	Organic (high fertility)	Organic (low fertility)	Non-organic	*P* value
Earthworm numbers				
Spring	25.9 (1.45)	21.3 (1.95)	14.9 (1.67)	0.01
Autumn	27.8 (3.33)	21.7 (2.34)	10.4 (1.08)	0.02
Nematode numbers (spring)				
Total	4861	4458	2240	0.08
General feeders	1044	1700	805	0.01
Monochids	193	215	91	0.01

Nematodes assessed: Rat-tailed Tylenchids (general feeders), Short speared Dorylaimes (general feeders), Rhabditids and Monochids.

Application of molecular biology techniques beyond that used in the current project (e.g. construction of gene libraries, terminal Restriction Fragment Length Polymorphism, nested FISH analyses etc.) would provide very useful information which could more fully elucidate the impact of organic farming, or other land management practices, on soil microbial populations. Future research into the microbiology of soils maintained under organic management should concentrate on using a molecular approach as core strategy. The issue of biodiversity of indigenous microflora in "organic" soils, and the implications of this for the sustainability of these ecosystems compared with soils under non-organic land management, should be the central focus of future research.

More conclusive data were found when earthworm numbers were counted (Table 11). A limited number of measurements were also made on the four sites of Field campaign 2 in spring 2000. Soil samples were collected and assessed for nematodes (Table 11). Significant differences were found between rotational positions for total (non-plant pest) nematodes, for general feeders and for monochids, with greater differences between organic v non-organic.

4. What are the nutrient pools and their sizes?

Literature review

The total pool of nutrients in organically farmed soil will be determined by the nutrient reserves inherited from the previous (non-organic) management and the current balance between inputs and outputs to the farm. In most cases, N balances for organic farms are positive, especially in predominantly grassland farms that include a high proportion of legumes and also import concentrate feeds. In these farms, imports of P and K in purchased feed are often sufficient to replace the nutrients exported in milk and livestock and lost in drainage. Farms with a higher proportion of cash crops are more likely to have negative balances, unless nutrients are replaced by fertilisers or brought-in manures. Whole-farm balance will be a poor indicator of the nutrient status of individual fields unless manures and other materials are allocated in such a way as to balance variations in crop offtake. The size of nutrient pools will also fluctuate during the fertility building and depleting stages of the crop rotation.

Nutrient pools in organically farmed soils are essentially the same as in non-organically managed soils but, in the absence of regular fertiliser inputs, nutrient reserves in less-available pools will be of greater significance. The main reserve of N is in soil organic matter and its availability is therefore closely linked to the microbial transformations and turnover of organic matter in the soil. The total N content of arable topsoils typically ranges from about 2 to 4 t N/ha. Organic farming practices would be expected to maintain the organic matter content of arable soils within the upper part of this range. Soils from long-term grassland contain more organic matter and more N, typically 5-15 t N/ha. Contents are similar in non-organically and organically managed grassland soils. The quality of the organic matter is also important. Recently immobilised N and plant residues are mineralised more rapidly than native organic N. Most N inputs in organic farming supply N to this organic pool, either as manures or crop residues or indirectly through biological N fixation. About 5% of soil organic N is in the most actively cycling fraction represented by the microbial biomass. The size of the biomass pool increases where organic matter is added to the soil but responses are only of moderate duration. At any time, only a small proportion of the N in soils is present as plant-available nitrate and ammonium ions, typically equivalent to 2 - 40 kg N/ha. In contrast, annual offtakes of N in crops are between 45 and 250 kg N/ha. During the growing season, the mineral-N pool is continually depleted by plant uptake and replenished by the mineralisation of organic-N. Nitrate will accumulate in the soil and increase the risk of loss if there is not an actively growing crop present to utilise the mineralised N. Animal manures and slurries with a high mineral-N content will add directly to this pool. In the upper soil layers of most agricultural soils, 3-14% of the total N occurs as non-exchangeable ammonium-N fixed in clay minerals. This is only slowly made available to plants but may be an important source of N in organically farmed soils.

Inorganic phosphates are present in soils in the soil solution, as definite P compounds and as surface films of calcium or iron/aluminium phosphates adsorbed on mineral particles. Phosphorus also exists as organic compounds, including P in the microbial biomass. This organic fraction accounts for 30 to 50% of the total P in most soils. Whereas N mineralisation is driven by the energy needs of the micro-organisms, P mineralisation is controlled by the supply of and need for P by the microbial population. The total P content of agricultural topsoils is typically 300 - 2000 kg P/ha. The inorganic-P compounds in soil are of limited solubility and as a result, phosphate concentrations in the soil solution are low, between 0.1 and 1 μg P/ml (equivalent to <0.01 kg P/ha). This is the pool that is available for plant uptake. As annual crop offtakes are usually between 10 and 35 kg P/ha, the soil solution must be continually replenished by dissolution of sparingly soluble P compounds and mineralisation of organic forms. Mineralisation of organic-P may be particularly important in organically farmed soils. Much of the reserve of inorganic-P will have accumulated as a result of fertiliser inputs during previous periods of non-organic management. Phosphorus fertilisers, such as rock phosphate, which are approved for use in organic farming will add to these pools of sparingly soluble-P. Much of the P in animal manures is present as insoluble calcium phosphates and will add to the inorganic pools in equilibrium with the soil solution. It is more difficult to build up reserves in sandy soils that have limited capacity to retain added P.

The main reserve of K is held in soil minerals, particularly primary micas and their weathering products that are generally the more important contributors of plant-available K in temperate soils. Clays and shales are rich in K whereas sandstones have relatively low contents. Organic forms of K are of little significance. The immediate source of K for plant roots is provided by K ions in the soil solution which are in equilibrium with K ions held on the cation exchange sites associated with clay minerals and the organic fraction of the soil. A less-readily available pool is provided by K ions trapped in the interlayer spaces of micaceous minerals. These ions are made available only slowly, in response to low K concentrations in the soil solution/exchange complex but may be of particular importance to the longer-term fertility of organically farmed soils. Typically soils contain about 40 - 500 kg/ha as exchangeable K and 25,000 - 50,000 kg/ha in non-exchangeable forms. In comparison, the annual offtake in crops is between 45 and 210 kg K/ha. As with P, much of the K in the less-readily available reserve pools may have originated from fertiliser applications during previous periods of non-organic management. Increased organic matter contents will increase the cation exchange capacity of organically farmed soils and hence the capacity to retain K in an exchangeable form. It is more difficult to build up K reserves in sandy soils that are lacking in K-rich minerals and have low cation exchange capacities. Manures and several of the fertilisers allowed for restricted use in organic farming will add to the soil solution/exchangeable K pool. Other, less-readily soluble, fertilisers add to the pool of fixed K.

The routine analytical methods used in non-organic agriculture for measuring the size of the plant-available pools of soil nutrients do not generally include a measure of the less-readily available forms and may therefore be less applicable to organic farming. Simple chemical tests are of limited value as they provide no information about the *rate* of nutrient supply. Furthermore, crops on organic farms <u>may</u> obtain a greater proportion of their nutrients from the deeper soil layers and sampling for assessments of soil fertility should reflect this.

There are no generally accepted methods for the routine determination of the supply of N from soil organic matter, in either non-organic or organic agriculture. However, incubation methods have been used with some success and are probably a useful guide to the N status of organically farmed soils. An additional determination of the content of fixed-ammonium may be of particular relevance to assessing the fertility of soils in organic systems.

The standard analyses used in non-organic agriculture for measuring plant-available-P do not include organic forms. As the supply of P from organic compounds is likely to be of particular importance in organically farmed soils, methods need to be modified to include this fraction. Current methods indicate that contents of extractable inorganic-P are often lower in soils from organic than from non-organic farms. Improvements in P availability arising from the activity of mycorrhiza will not be detected by chemical extraction techniques.

Routine analyses of plant-available K generally measure the exchangeable and soil solution K in the soil. When measured in this way, contents in organically farmed soils are often similar to those in non-organically farmed soils. Including a measure of fixed K often improves the precision of the estimates in non-organic agriculture and is likely to be of particular benefit with organically farmed soils.

Total contents of nutrients will be determined by the nutrient reserves inherited from the previous non-organic management and by the nutrient balance for the current organic system. Balances are likely to be positive in livestock farms feeding purchased concentrates and more likely to be negative for farms with a higher proportion of cash crops. The less-readily available nutrient pools are particularly important for maintaining the supply of nutrients to crops in organic rotations and analytical methods to determine contents of available nutrients in organically farmed soils should reflect this.

Because the largest S pool in the soil is the organic matter, supply to crops is dependent on microbial action to mineralise organic S to sulphate. Thus there are many similarities between N and S cycling in soils.

Essential trace elements for plants are iron (Fe), magnesium (Mg), manganese (Mn), copper (Cu), zinc (Zn), boron (B), molybdenum (Mo) and chlorine (Cl). Others (e.g. iodine (I) and selenium, Se) do not appear to be necessary for plant growth, but they are essential for animal health, so that their uptake is beneficial in fodder crops. Micro-nutrients are taken up via the soil solution, and so will move to the plant root either by mass flow or by diffusion. They are rarely present in ionic form, usually being complexed with inorganic or organic ligands. Their concentrations in the soil solution are at the micro-molar level and, it is fair to say, that our understanding of their uptake and behaviour in the soil solution is less than complete. The rhizosphere will, of course, also influence their speciation and uptake: again, this is poorly understood.

Soils are rarely deficient in a trace element (with a few exceptions; e.g. cobalt deficiency on soils naturally low in Co); it is the availability of the trace metal to the root that might restrict uptake. This is usually associated with soil conditions (adverse pH, drainage, and consolidation). Therefore, maintaining good soil conditions will minimise the risk of trace element deficiencies.

Measurements

Nutrient pools were measured using standard analytical techniques as used for providing advice in non-organic farming (e.g. MAFF, 1986). However, to examine the potential for differences in other nutrient pools, a variety of other analyses were also used (methods summarised in Table 1, results in Table 12). Our findings confirm that for P, K, Mg and S, there is, on average, no major differences within organic rotations or between non-organic and organic systems: as has been stated several times, nutrient pool size will depend on the balance of inputs and outputs. Furthermore, the PK pools as measured using standard techniques change only slowly with time (Archer, 1985). It should therefore be no surprise that differences in these pool sizes were not detected. The standard errors associated with the means suggest a wide range of values: this would be expected considering the widely different inputs that we recorded from the farmer information.

Nitrogen, however, is quite different. Nitrogen cycling is predominated by transformations of organic N. Levels change relatively quickly and it with this nutrient we might expect to find the largest differences within an organic rotation and between non-organic and organic systems.

Table 12. Properties of soils from fields at 'high' and 'low' stages of fertility stages of the rotation on organic farms and from non-organic farms (excluding grassland farms): means & standard errors.

		Organic high fertility	Organic low fertility	Non-organic	*P* value
Field campaign 1 – Autumn 1999 (n=23)					
pH		7.5 (0.13)	7.6 (0.12)	7.7 (0.10)	0.12
Exch. K	(mg/kg)	268 (31)	269 (34)	286 (42)	0.87
HNO_3-K	(mg/kg)	940 (76)	845 (68)	969 (93)	0.34
Water-soluble P	(mg/kg)	4.6 (1.25)	4.8 (0.92)	5.1 (1.58)	0.94
Olsen P	(mg/kg)	28 (4.5)	31 (4.0)	33 (4.9)	0.59
16h-Olsen P	(mg/kg)	97 (13)	105 (10)	98 (12)	0.81
Total P	(mg/kg)	887 (48)	969 (75)	924 (65)	0.47
Exch. Mg	(mg/kg)	150 (22)	149 (24)	151 (26)	0.99
Ext. S	(mg/kg)	10.2 (1.36)	9.1 (0.66)	8.6 (1.18)	0.46
Total S	(mg/kg)	440 (34)	425 (30)	438 (37)	0.89
Field campaign 2 – Spring 2000 (n=4)					
Olsen P	(mg/kg)	8 (4.4)	9 (0.7)	9 (1.3)	0.93
16h-Olsen P	(mg/kg)	54 (13.0)	55 (5.2)	51 (6.6)	0.95
Exch. K	(mg/kg)	147 (19.2)	166 (29.5)	170 (22.5)	0.91
HNO_3-K	(mg/kg)	830 (124)	846 (97)	991 (165)	0.29

Tables 9 and 10, earlier, reported our measurements of LFOM and PNM (measured by anaerobic incubation). These reflect important N pools in the soil. The more labile SOM contributes to N dynamics and it is this fraction that warrants more attention. Rates of N turnover were within the published range (1-10% of total soil N). Since none of the non-organic soils had a higher N turnover than the organic soils, it suggests that the supply of N in organic systems is maintained by higher rates of mineralisation, at least in the high fertility phase. This may reflect differences in the quantity, or quality of labile sources of SOM, but does not indicate the sources of OM involved. In this study, analysis of the LF showed that it could not account for the entire N released by PNM. Biological degradation (PNM) of OM and physically harsh extractions (hot water) may, therefore, be more effective in accessing other protected forms of OM than were recovered in the LF by sonication. Future work should, therefore be directed towards more detailed studies of other components of labile OM, including the ‘protected’ intra-aggregate LF and organo-mineral (*viz*. silt-clay) complexes and the contribution from the microbial biomass.

5. Do organically managed soils have a greater inherent capacity to supply nutrients?

Literature review

It is likely that organically farmed soils will have a greater inherent capacity to supply nutrients than the majority of non-organically farmed soils simply because a key objective of their management is to build up nutrient reserves and increase the supply of nutrients from the soil's own resources. However, if a rotation is such that nutrient offtakes consistently exceed inputs, then nutrient supply will decline.

In the case of N, increased supply is largely achieved through the accumulation of organic matter in the soil during the ley (‘fertility building’) phase of the rotation and subsequent utilisation of the organic-N during the arable cropping (‘exploitative’) phase. Organic management practices have less effect on organic matter contents and other properties of grassland soils. Thus, improvements in inherent fertility should more strictly be considered to be confined to comparisons between arable soils. In many respects, however, these are benefits of mixed farming and ley-arable systems rather than being confined solely to organic agriculture.

Long-term fertility will be determined to some extent by the total content of nutrients in the soil. As organic farming seeks to minimise inputs, total contents of nutrients such as P and K are unlikely to be greater in organically farmed soils than under their previous non-organic management. Indeed, much of the inherent fertility of these soils is likely to be due to accumulations of residual P and K from earlier fertiliser applications if they were farmed non-organically. Improvements in the inherent capacity of organically farmed soil to provide P and K are therefore most likely to be due to a greater proportion of the nutrients being retained in the actively cycling pool rather than due to increases in the total content.

Although some organic farms appear to function satisfactorily with negative P and K balances, this will deplete the total nutrient content in the long-term and represents a reduction in the inherent fertility of the soils.

Ley-arable rotations in organic farming (and other mixed farming systems) will increase the supply of N from soil organic matter but benefits will decline towards the end of the arable phase. Potassium and P contents are unlikely to be increased (but this depends very much on the long-term balance between nutrient inputs and offtakes); however, a greater proportion may be present in the actively cycling pools.

Measurements

Table 12 above suggests, on average, no major differences in the pools of P, K and other nutrients in the differently managed soils, reflecting the assertions from the literature of only slow changes in pool sizes and the effects of P and K balances. This was also confirmed by sequential measurements taken during summer 2000 (see later).

The main differences, however, are likely to be with N supply because of the more labile nature of this nutrient. Again, evidence already provided (e.g. Table 9) has shown that the potential for N supply from the organic fraction (as measured by PNM) is greater at the start of the arable rotation than at the end (unsurprisingly), and that N supply at the end of the rotation is similar to non-organic arable soils. This was also confirmed by crop N uptake data during summer 2000 (Fig. 5, later). However, this does not necessarily mean a greater *inherent* capacity of organically farmed soils to supply N: indeed it is more likely to be an effect of ley-arable farming than whether non-organic or organic.

However, the series of incubation studies possibly suggest that some soils are more able to degrade crop residues than others. This was tested by incubating different soils under controlled laboratory conditions at optimum temperature and moisture conditions with and without an added crop residue. Incubation experiment 1 developed this approach and compared organic and non-organic soils (Fig. 3). The size of the mineral N accumulation is a measure of the ability to mineralise the added residue. Non-organic soils from Farms 1 and 3 performed less well than the organic counterpart (Fig. 3b) and, interestingly, these soils held less extractable ATP than the organic equivalents (Fig. 3a, absolute differences between farms are due to soil texture influencing recovery of ATP). The data suggest that these non-organic soils were under-performing, rather than the organic management showing enhanced degradation.

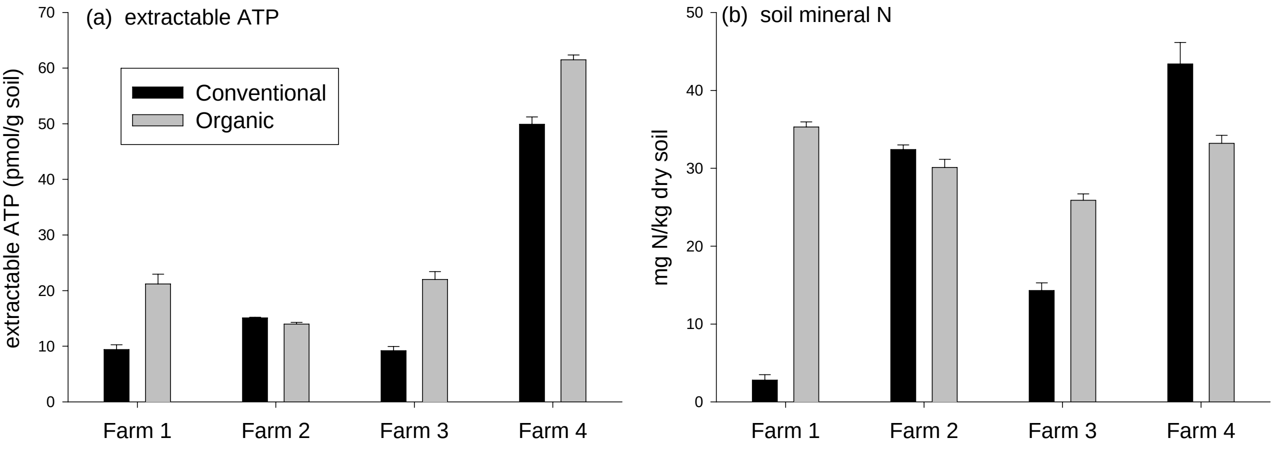


Figure 3. Data from Incubation experiment 1. Relationship between extractable ATP and the ability of each soil to mineralise an added clover residue. Two fields from four farms sampled. Farms 1 to 3, organic (high fertility) and non-organic fields, Farm 4 – non-organic farm with and without regular additions of FYM

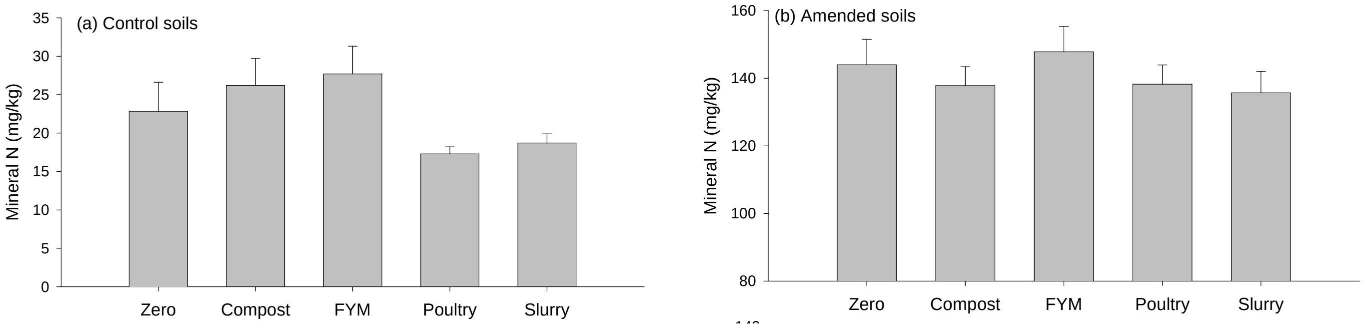


Figure 4. Data from Incubation experiment 2. Soil mineral N accumulation after 12 weeks incubation, with and without added clover residue. Soils had received previous applications of different organic amendments, as shown.

Figure 4 shows the results from the same experimental method repeated in Incubation experiment 2, with soils receiving different organic amendments (further details of soil organic matter are shown in Table 10, above). The soil had been managed organically for several years. In this case, there were no differences in the soils' ability to degrade the added residue (Fig. 4b), with about 40% of the residue N mineralised after 12 weeks. There were, however, no differences in extractable ATP levels between soils. The control soils (Fig. 4a) showed differences in N release, reflecting the size of the N pools derived from previous amendment applications.

Incubation experiment 3 used the same procedure to compare organic (high and low fertility) and non-organic soils from 6 sites, albeit only incubated for 4 weeks (to see if the method had potential as a screening process). The method again picked up differences between soils in their ability to mineralise the added residue, though differences were not restricted to a particular rotational position: one high fertility, two low fertility and one non-organic soil did not mineralise at the expected rate.

The consequence of this work is that differences in N cycling occur between soils. Part of this, is of course due to the quality of organic inputs. However, it seems that some soils are more capable of mineralising than others. Further, more detailed work, is justified on this aspect.

6. What are the processes and rates of nutrient transfer in relation to nutrient demand?

Literature review

The same processes operate in organically farmed soils as those that are farmed non-organically although their relative importance and rates may differ. There are some indications that biodynamic practices offer benefits above those provided by other forms of organic farming. If proven, any such benefits would be difficult to explain in terms of our current understanding of soil processes.

Nitrogen availability is generally considered to be the limiting factor that determines the productivity of organic systems. The limited published information that is available provides little direct evidence that decomposition of organic matter or recycling of N is more rapid in soils that have been managed organically (our work, described above, suggests this ability can be restricted in some soils: we see no evidence of enhanced degradation in any soil). In the absence of regular fertiliser inputs, contents of mineral-N will generally be lower than in non-organically farmed soils. Thus, crop yields are usually lower from organic systems. Nitrogen availability and crop yield, however, are strongly influenced by the design and stage of the cropping rotation. Mineralisation of soil organic matter may supply as much N to the first crop following cultivation of a ley as that provided by fertiliser on non-organic farms. In contrast, much less N will be available at later stages of the arable phase of the rotation. Leguminous crops are less dependent upon the supply of N from the soil and may produce yields comparable to those under non-organic management; however, fixation in grass-clover swards is insufficient to produce yields equal to those of intensively fertilised grassland.

Although large quantities of N can be made available from the cultivation of leys or green manures in organic systems, it may be difficult to utilise this N effectively and match the rate of N-mineralisation to the pattern of crop demand. Mineralisation in spring may occur too late to supply the N required during the early growth of the crop and, particularly with crops that have a short growing season, may continue into the summer and autumn when the crop no longer has a requirement for N. Improvements in the ability to predict rates of mineralisation would improve the efficiency of N use and reduce losses. Short-term N supplies can also be manipulated by strategic applications of manures and slurries but, here too, efficiency is limited by uncertainties about nutrient content, uncontrolled losses and rates of mineralisation. Catch crops can be grown to utilise N that is mineralised later in the season and would otherwise be lost but similar information about the decomposition of the catch crop residues is required if the conserved N is to be utilised effectively by the following crop.

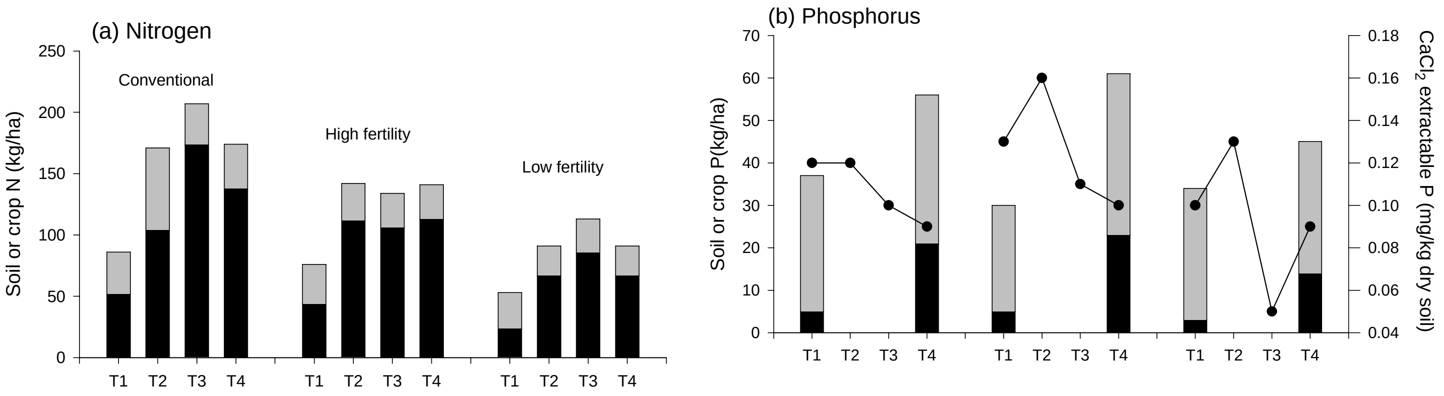
If N availability limits crop yields from organic systems, there are likely to be lower requirements for other nutrients than in non-organic systems. There is evidence from nutrient budgets that organic systems can function with lower inputs of P and K than would be expected for comparable fertiliser-based systems. Simple budgets, however, only provide information about total quantities of nutrients. Understanding the fertility of organically farmed soils requires information about the dynamics of uptake and conversion of nutrients to plant-available forms. This has not been studied in detail. Crops that are growing more slowly will not deplete the available pool of nutrients as rapidly. In these circumstances, the dissolution of inorganic-P compounds, mineralisation of organic-P and slow release of fixed K may be sufficient to replenish the immediately available pools and meet the demands of the crop. Maintenance of low concentrations in the soil solution will increase concentration gradients and shift the equilibrium towards these more available forms. Phosphatase activity has been shown to be greater in P-deficient soils. However, the increased activity was insufficient to meet crop demands. In organically farmed soils, access to limited supplies of nutrients may be increased by greater mycorrhizal activity. The fungal hyphae effectively increase the volume of soil in contact with the roots. In this respect, mycorrhiza will increase the rate of removal of soil P from the bulk soil rather than increasing the total amount available. However, there is also evidence that mycorrhizal roots are able to absorb P from solutions at lower concentrations than non-infected roots. This would tend to increase the total reservoir of potentially available P and other nutrients in the soil.

The short-term availability of P and K may be increased by applications of manures and slurries at appropriate stages of the crop rotation. Much of the P and particularly the K in farm slurries is readily available. Similarly, incorporation of green manures, while not representing a net input, will increase the availability of P and K compared with other sources in the soil, and may redistribute nutrients in the profile where they are more accessible to crops. Studies indicate that P and K from animal manures and green manures may either be as effective as inorganic fertilisers or where they have less immediate effect, be of greater residual value. Slow-release forms of K fertiliser may prevent luxury uptake of K by crops but, even in organic agriculture, much of the K is in readily soluble forms and any such benefits are likely to be small. Grass-clover leys that are cut for silage remove particularly large quantities of P and K and probably make the greatest demands on nutrient pools during an organic rotation. Clover is a poor competitor with grass for nutrients and its growth will be suppressed if P or K is in short supply. Unless sufficient nutrients are returned in slurry or manure, P or K may become the nutrient limiting production through their indirect effect on clover growth, acting to limit the quantity of fixed N entering the system. Animal manures can also provide additional nutrients at other stages of the rotation where there are particularly high demands.

Measurements

Data already presented support these findings. Sequential measurements taken through summer 2000 also allowed us to examine the interaction between crop uptake and soil N, P and K status. Figure 5 summarises effects, as a mean of the four sites, for simplicity. Nitrogen levels show differences between the high and low fertility N supply. Non-organic is highest because of fertiliser additions. Background soil mineral N levels are fairly constant, suggesting that these are baseline levels. Because mineral N is not accumulating under the lower yielding cereal crops, this suggests that N is limiting the yields. The effects are less straightforward with P and K. The data confirm previous findings that extractable P and K levels in soils, measured by non-organic methods, can be similar through the rotation, (though Fig. 5 possibly provides some evidence of a decline in K during crop growth), and between non-organic and organic systems.

In addition, calcium chloride extractions were made on the topsoil (0-30 cm) and analysed for P and K. This was used as a more sensitive indicator of potential changes in soil P and K supply. These data suggest a reduction in P and K pools through the growing season, though differences between rotational position were inconsistent (Fig. 5).



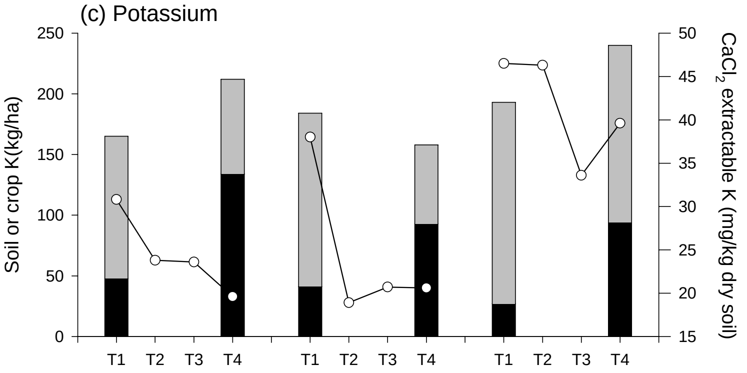


Figure 5. Changes in soil and crop N, P and K with time, average of four sites, spring/summer 2000. Dark bars are crop uptake (cereal plus weeds), light bars are soil nutrient level (kg/ha, 0-30 cm), sampled in spring and at harvest of the cereal crops. The circles for P and K are the calcium chloride extractable P and K levels (0-30 cm) through spring and summer.

7. How are the above affected by various fertility building or fertility depleting activities?

Literature review

Soils should contain sufficient organic matter and biological activity to provide the N required to produce adequate crops throughout the rotation. It is equally important that this N should be released at times when it is needed by the growing crop.

Nitrogen is likely to be the nutrient that limits the yield of arable crops, with organic rotations relying mainly on N fixed and accumulated through the ley ('fertility building') phase. It is the fresh returns of organic matter (the active fraction) that has most impact on the subsequent N supply. Thus without the addition of mineral N (e.g. from animal manures), crop need must be met by mineralisation of organic N.

Whereas the N supply will be greatest immediately after the ley (fertility building) phase, the active soil organic matter pool will become depleted as it mineralises and is utilised by the growing crop or is lost from the system by leaching. Without supplementation (by manure, for example), it is likely that the N supply will become more limiting with length of the arable phase. Phosphate and potash supply is likely to be less affected by rotational position. As N supply and yield decrease, P and K demands will also decline, so that these nutrients are even less likely to become limiting.

Measurements

Confirmatory data on this aspect have already been provided above. Our data confirm that there seems to be little effect of the stage of rotation on P and K. In spite of fewer external inputs, soil contents were comparable to those on non-organic farms. The main effects are on N, with a lager N supply after ploughing the fertility building ley compared with later in the rotation. Our measurements suggest that the level of inherent N fertility at the end of the fertility depleting stage is similar to non-organically managed arable soils.

8. What are the environmental consequences of organic management?

Many studies and reviews of the environmental implications of organic farming have been completed. This therefore warrants less attention here. However, the general conclusion is that N leaching losses are less than from non-organic farming, when averaged over the rotation: the autumn breaking of leys has been identified as the main source of nitrate loss. Manures can be a source of nitrate, so that applications of manures with a large ammonium-N component should be avoided in the autumn. Ammonia losses from cattle housing, manure storage and spreading represent an important loss of nutrient as well as being an environmental threat. Composting can exacerbate ammonia losses compared with stacking the manure. Rapid incorporation of the manure after spreading will minimise ammonia losses. Farm N balances are a useful guide to the potential environmental risk of farming systems: organic systems generally have smaller surpluses than non-organic farms.

9. What are the implications of our findings for the better management of soils on organic farms?

Techniques that will optimise nutrient recycling and the maintenance of all aspects of soil fertility include:

- having a better knowledge of nutrient transfer rates.
- adopting appropriate soil cultivation methods and timeliness to maintain soil structure (i.e. optimising for soil biological activity).
- maintenance of soil drainage and soil pH.
- frequent return of organic matter (manures/crop residues).
- use of cover crops and catch crops wherever possible.
- avoidance of autumn cultivation of leys.
- the use of carefully planned rotations.
- regular soil sampling for determination of soil P and K status (by appropriate analytical procedure)

Further research is required to better understand the processes involved to optimise the use of these strategies. Further understanding and quantification of nutrient transfer processes (from soil pools to plant uptake) and rates of these processes is particularly important, and would improve our understanding of non-organically managed soils also.

CONCLUSIONS

Organic farming recognises the soil as being central to a sustainable farming system. Soil fertility is determined by a set of interactions between the physical and chemical environments of the system and by biological activity. Organic matter is linked intrinsically to soil fertility, because it is important in maintaining good soil physical conditions and also contains most of the soil reserve of nitrogen and large proportions of other nutrients such as phosphorus and sulphur.

Field management data gathered from farmers showed, however, that organic matter returns are not necessarily larger in organic systems. Many non-organic systems receive regular manure applications and higher yielding non-organic crops may return larger crop residues. Conversely, many organic systems receive little or no manure, relying on the fertility building ley phase for organic matter input. Management practices within organic and non-organic systems are diverse and, sometimes, overlapping with consequences for soil fertility.

Soil physical effects

Root restriction is most likely to limit crop productivity if the supply of nutrients (and water) is limiting. It is therefore particularly important that roots in organic systems are able to fully exploit the complete soil volume.

Whilst addition of SOM generally promotes an increase in soil aggregate stability, it is generally the younger SOM with a larger content of polysaccharides, roots and fungal hyphae that stabilises aggregates. Fungal hyphae (the biological agent) and extracellular polysaccharides (major cementing agents, deriving from plants and soil bacteria) are capable of linking together mineral particles to form aggregates. In addition, mucigels are released by growing roots and rhizosphere microflora.

Thus, the most significant SOM components in agronomic systems are transient materials that exert their effect for one year at most. This correlates with the observation that aggregate stability is greatest under grass, where there is continuous production of these components, and decreases rapidly under arable cultivation. This suggests that optimal aggregate stability requires the frequent turnover of transient organic residues. Therefore, a ‘biologically active’ soil is better predisposed to better aggregate stability.

Humic substances also provide some long-term stabilisation of structure. Well-decomposed, composted materials induce a more steady increase in aggregate stability because they consist of humic substances which are stable binding agents. Materials that add lignin and other humic-like materials also tend to have longer lasting effects.

Our measurements generally showed better structure soon after ploughing the fertility building ley. On average, comparisons with non-organic systems did not show organically farmed soils to be consistently better or worse in terms of structure.

Soil biology

The soil hosts complex interactions between vast numbers of organisms, with each functional group playing an important role in nutrient cycling: from the macrofauna (e.g. earthworms) responsible for initial incorporation and breakdown of litter through to the bacteria with specific roles in mobilising nutrients.

The complexity of soil food webs emphasises the diverse populations of soil organisms involved in nutrient turnover. An additional advantage of maintaining soil biodiversity is the potential for protection against plant damaging organisms. Earthworms have many direct and indirect effects on soil fertility, both in terms of their effects on soil physical properties (e.g. porosity) and nutrient cycling through their effects on micro-floral and -faunal populations (density, diversity, activity and community structure). Organic farming’s reliance on soil nutrient supply requires the presence of an active meso- and macro-faunal population. Organic management practices are expected to encourage active earthworm (and, presumably, other soil macro-arthropod) populations.

Our simple measurements showed more earthworms under the organic systems (compared with non-organic) and generally more worms immediately after a ley compared with later in the rotation. We also found evidence of more beneficial nematodes in organic systems.

Soil microbial biomass

The soil microbial biomass acts as a labile source and sink of C, N, P, and S and an agent of nutrient transformation and pesticide degradation. In addition, micro-organisms form symbiotic associations with roots, act as biological agents against plant pathogens, contribute towards soil aggregation and participate in soil formation.

Generally, organic farming practices have been reported to have a positive effect on soil microbial numbers, processes and activities. Much of the cited literature has made direct comparisons between organic/biodynamic and non-organically managed soils. The evidence generally supports the view of greater microbial population size, diversity and activity, and benefits to other soil organisms. However, little is currently known about the influence of changes in biomass size/activity/diversity on soil processes and rates of processes. Nor is it possible to conclude that all organic farming practices have beneficial effects while non-organic practices have negative effects. In the few arable comparisons where a lack of differences or greater activity were found in the non-organic system, this might be related to greater residue returns in the non-organically fertilised system. If so, this provides a pointer that where differences do occur, the key factor that differentiates between non-organic and organic systems is the return of organic matter.

Our measurements indicated that there were differences between the levels of readily-extractable ATP in soils managed under organic and non-organic regimes but differences in soil microbiology were subtle rather than dramatic.

Nutrient cycling

Organic farming seeks to build up the reserves of nutrients in the soil while at the same time reducing inputs. Because of changes during the fertility-building and fertility-depleting stages of organic rotations, it is difficult to define the overall fertility of an organically farmed soil from measurements at a single stage of the rotation. It is also more important to include measurements of the reserves of less-readily available nutrients (e.g. organic P and non-exchangeable K) in assessing fertility than with non-organically farmed soils.

Nitrogen
Nitrogen supply from the soil is mediated predominantly by the biomass. Because of the importance of the organic N pool and of microbial transformations, the availability and fate of N is closely linked to the turnover of organic matter in the soil. Soils should therefore contain sufficient organic matter and biological activity to provide the N required to produce adequate crops throughout the rotation. It is equally important that this N should be released at times when it is needed by the growing crop. It is particularly important to include measurements of other less-readily available forms (e.g. fixed ammonium ions) of N in assessments of the N status of organically farmed soils. Crops on organic farms may also obtain a greater proportion of their nutrients from the deeper soil layers and sampling for assessments of soil fertility should reflect this. Differences are more apparent with arable than with grassland soils because the latter usually have higher organic matter contents, irrespective of whether they are managed non-organically or organically.

Phosphorus
Soil P supply relies both on microbial action on organic P sources and on chemical transformations within the soil. The low concentrations in the soil solution are depleted rapidly during periods of active plant growth and must therefore be replenished continually from the organic and inorganic pools to maintain adequate supplies to the root. The concentration of P in the soil solution is largely determined by the sorption/desorption reactions of surface coatings of calcium phosphates in alkaline soils and of iron/aluminium phosphates in more acid conditions. Similarly, there will be competition between these sorption sites and plant roots for the P released into the soil solution from the decomposition of organic compounds. The supply of P from organic compounds is likely to be of particular importance in organically farmed soils and assessments of soil fertility should include a measure of this pool. Consequently soil P analytical methods must be able to interpret situations where measurable pools are small and P cycling, rather than pool size, is the major determinant of productivity. Changes in P availability arising from the activity of mycorrhiza will not be detected by the chemical extraction techniques commonly used for determining plant-available P in the soil.

The large reserves of P that have accumulated under non-organically managed fields may act as a source of P when farms are first converted to a less-intensive, organic management. Understanding the fertility of these soils will require information about the size of this pool and its contribution to plant uptake.

Potassium
The quantities cycling in agricultural systems are of the same order as those of N. However, unlike N and P, the behaviour of K is dominated by its inorganic chemistry and organic forms are of relatively little importance. The role of fixed K to plant nutrition might be especially important for organic systems. There is a need to take full account of K dynamics and the rate of release from less-readily available pools, rather than simply measuring the content of available K at one particular time. Careful management of nutrients to replace the large removals of K from cut grassland is particularly important in organic systems where there is great reliance on the N fixed by clover. Potassium is particularly important in organic systems as it is only possible to have vigorous clover growth if the K supply is adequate.

Our measurements of a range of different nutrient pools reflecting short- and long-term supplies found no consistent differences for P and K within organic rotations. In spite of fewer external inputs, soil P and K contents were similar to those in non-organically managed soils. We conclude that nutrient supply is governed by soil reserves that have developed as a result of previous managements and of current P and K inputs and offtakes. In the absence of soluble fertilisers, N supply was also governed by history of inputs, particularly recent inputs of labile organic sources (leys, manures). There was an indication from incubation studies that some soils were better predisposed to mineralising the organic N, though effects were not consistent within or between farming systems. Further work is warranted on this aspect.

The role of the plant

Plants play important roles in nutrient cycling other than simply through nutrient uptake. Cover crops retain nitrogen that would otherwise be leached from the soil, and recycle it when incorporated into the soil. The return of crop residues is central to nutrient cycling, the carbon being a food source for the soil microbial biomass. The rhizosphere plays an important role in nutrient transformations, not least by solubilisation of plant nutrients. Plants compete with soil micro-organisms for recently mineralised nutrients that might otherwise be immobilised and become available for crop growth. Uptake creates diffusion gradients, resulting in the release of nutrients into the soil solution from soil particles.

All of these processes occur in non-organically and organically managed soils but they are potentially more important in the absence of water-soluble fertiliser inputs. Organic and non-organic soils differ in two further respects. First, yields are generally lower on organically managed soils, so that the nutrient sinks are smaller. Second, is the importance of the role of mycorrhiza. Mycorrhiza can increase nutrient uptake by crops but are less abundant in soils that receive inputs of water-soluble P fertilisers and fungicides.

Phosphorus budgets for organic farms frequently indicate small deficits. With the exception of soils with low P sorption capacities and reserves, these deficits are not reflected in declining contents of extractable P in the soil, suggesting that organic farms may be mining reserves derived from earlier fertiliser applications. Nutrient budgets indicate significant deficits of K on some organic farms but this is least likely on livestock farms that import animal feed and straw. Except on sandy soils with low K reserves, concentrations of extractable K appear to remain relatively stable in soils that are farmed organically. Assessments of the fertility of these soils should include a measure of fixed-K.

PRACTICAL IMPLICATIONS FOR DEFRA

This project has provided useful background information on managing soil fertility in organically managed systems. It confirms the importance of fresh organic returns that benefit all aspects of soil fertility. This is as equally applicable to non-organic systems, of course. Furthermore, it can be concluded that although nutrient management in organically managed soils is fundamentally different to soils managed non-organically, the underlying processes supporting soil fertility are not. The same nutrient cycling processes operate in organically farmed soils as those that are farmed non-organically although their relative importance and rates may differ. Nutrient pools in organically farmed soils are also essentially the same as in non-organically managed soils but, in the absence of regular fertiliser inputs, nutrient reserves in less-available pools might, in some circumstances be of greater significance.

The information gathered during this project now needs to be provided in a usable form to growers and advisors. The project has gone some way to making the information available. However, we suggest that a booklet is produced, summarising the main findings and their implications for best management of organically farmed soils.

TECHNOLOGY TRANSFER

1. Presentations

- 2 Presentations at HDRA/HRI Soil Fertility Day (*c.* 100 delegates), September 2000, Wellesbourne
- Presentation to organic farmer group, High Mowthorpe (*c*. 50 delegates)
- 3 Presentations at SCI/ADAS/BSSS Meeting, November 2001 (*c*. 120 delegates)
- 2 FACTS training days (*c*. 50 delegates)
- Poster at AAB meeting, December 2000 ‘Rotations for the New Millennium’
- 3 Posters/presentations at UK Organic Research Conference, spring 2002

2. Papers/reports

Shannon, D., Sen, A.M. & Johnson, D.B. (2002). A comparative study of the microbiology of soils managed under organic and conventional regimes. *Soil Use and Management* (in press).

Shepherd, M.A., Harrison, R. & Webb, J. (2002). Managing soil organic matter – implications for organic farming. *Soil Use and Management* (in press).

Stockdale, E.A., Shepherd, M.A., Fortune, S. & Cuttle, C.P. (2002). Soil Fertility in organic farming systems – fundamentally different? *Soil Use and Management* (in press).

Watson, C.A., Atkinson, D., Gosling. P., Jackson, L.R. & Rayns, F.W. (2002). Managing soil fertility in organic farming systems. *Soil Use and Management* (in press).

Shepherd, M.A., Hatley, D., Gosling, P., Rayns, F., Cuttle, S. & Hatch, D. (2000). Soil fertility in organic farming systems - are there fundamental differences between organic and conventional farms? *Aspects of Applied Biology* **62**, 113-118.

Hatch, D., Shepherd, M. & Hatley, D. (2002). Understanding soil nitrogen supply: organic matter quality and quantity. In: *Research in Context, Proceedings of the UK Organic Research 2002 Conference* (Ed J. Powell), pp. 145-146.

Shepherd, M.A., Hatley, D. & Gosling, P. (2002). Assessing soil structure in organically farmed soils. In: *Research in Context, Proceedings of the UK Organic Research 2002 Conference* (Ed J. Powell), pp. 143-144.

Gosling, P. & Shepherd, M.A. (2002). Theory and reality of organic soil fertility – organic matter. In: *Research in Context, Proceedings of the UK Organic Research 2002 Conference* (Ed J. Powell), pp. 137-138.

3. Website

www.adas.co.uk/soilfertility was set up to publicise the project and to also allow downloading of the literature review. The site describes the project objectives, project consortium and conclusions from the literature review. Each Chapter of the review was converted to a .pdf file and each can be separately downloaded from the website. Statistics about visitors have been collected over the last year. These show that the site has been well visited and well used.

In summary, the site has been looked at 2,750 times by 1,568 people, of which 1,243 visited just once. There were good results for the downloading of the .pdf files, summarised in the table below:

	Page	Subject	Hits
1	http://www.adas.co.uk/ soilfertility/biblio.pdf	Bibliography	2,525
2	http://www.adas.co.uk/ soilfertility/soilbiol.pdf	Soil biology	1,624
3	http://www.adas.co.uk/ soilfertility/summary.pdf	Report summary	1,018
4	http://www.adas.co.uk/ soilfertility/SOILMANA.pdf	Organic management	857
5	http://www.adas.co.uk/ soilfertility/Nutrient.pdf	Nutrient cycling	944
6	http://www.adas.co.uk/ soilfertility/SOILPHYS.pdf	Soil phyiscal properties	634
7	http://www.adas.co.uk/ soilfertility/Recommen.pdf	Recommendations for research	477
8	http://www.adas.co.uk/ soilfertility/introduction.pdf	Introduction to review	391

The site which gave us the most referals through links on their page was www.organic-research.com. The Bangor University search engine also seemed to serve us well.

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