RESEARCH TOPIC REVIEW: The role, analysis and management of soil life and organic matter in soil health, crop nutrition and productivity

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1. Scope and Objectives of the Research Topic Review:

The objective of this research review is to draw together available relevant research findings in order to develop the knowledge and expertise of organic advisers and thereby to improve soil management practice on organic farms. The Review will focus on the role analysis and management of soil life, and:

1. Identify all the relevant research undertaken
2. Collate the results of research and summarise the findings of each project
3. Draw on practical experience
4. Analyse the research and summarise the conclusions in a form that is easily accessible by advisers and can be applied to their soil related work on farm.

In particular the review will:

- Summarise briefly the role of all soil life and focus on issues that have been identified in research.
- Identify all soil life analytical protocols and focus on any that have been identified in research.
- Identify how soil life can be influenced by farm management practices.

2. Key points arising from the review

Roles of organic matter and soil life

- The interactions of soil OM and soil organisms are critical for food and fibre production particularly with regard to: nitrogen fixation; transmission and prevention of soil-borne crop disease; interactions with plant roots; decomposition of organic substrates; and the transformation of nitrogen (N), phosphorus (P) and sulphur (S) through direct and indirect microbial action.
- 80-90% of all soil processes result from the interaction of soil organisms and OM.
- OM in soils includes materials cycled within the soil for hundreds of years as well as materials added recently through e.g. root exudation, crop residues, manures …
- The OM content of soils is controlled by the balance between inputs of OM and rates of decomposition by soil organisms.
- Total OM in soil may be a poor guide to function. It is the ‘fresh’ or ‘active’ fractions of SOM that seem to be more important in affecting key soil properties.
- The soil is home to organisms of all shapes and sizes making up 1-5% of soil OM.
- There is a strong correlation between the total OM content of soil and the size of the soil microbial biomass population; as OM contents increase the size of the populations and activity of soil organisms also tends to increase.
- Soil OM is the main food resource for soil organisms as most rely on decomposition of the complex organic materials, which comprise the soil OM, to obtain energy. Soil organisms possess the enzymatic capacity to breakdown virtually all organic compounds added to soil.
- Soil organisms not only occupy soil; they are a living part of it and as a result of their interacting activities also change it and have a key role in soil structure formation and stabilisation.

Analysis methods for organic matter and soil organisms

- There are a number of routine analytical methods for soil OM including combustion and chemical oxidation methods. Currently dry combustion at temperatures >900 ˚C is considered to give the most reliable determination of total soil C, as long as correction for carbonate is carried out.
- Most methods determine soil organic C; results may also be reported as soil OM.
- Methods determining either light fraction OM or particulate OM measure the pool of relatively fresh, undecomposed plant residues. There are no routine analytical methods for labile soil OM; further developments are needed before such measurements become cost effective.
- Measurements of soil organisms and/or other biological parameters are not routinely measured in the UK or elsewhere in Europe. Some soil monitoring programmes include estimates of the capacity of the soil to supply nutrients as a result of biological processes, as well as measurements of the size of the soil microbial biomass and determination of some soil mesofaunal groups.
- Direct counting of bacteria and/or fungi in soil is not reliable and fraught with errors of calibration and interpretation. Extraction and characterisation of DNA from soil is likely to provide cost effective approaches for the identification of individual species, groups or communities of soil organisms in the next decade.
- Determination of the size of the soil microbial biomass as a single entity is possible; fumigation-extraction methods are robust and routinely used in monitoring. This methodology allows estimation of the amount of carbon, nitrogen, sulphur, or phosphorus associated with the soil microbial biomass.
- Expanding opportunities are becoming available for measurement of soil biodiversity following extraction of DNA from soil, especially with the development of molecular tools. Caution is still required in interpreting the data obtained with these methods.
- Microbial activity can also be estimated in controlled incubations or via biochemical determination of the activity of a number of key enzymes.

Interpretation of analysis data to guide management

- Many authors argue that maintenance and enhancement of soil biological fertility is of benefit within all agricultural systems. However, there is no clear guidance on how soil analysis of any biological parameter could be used to support management decisions in practice.
- The maximum potential soil OM content at any site is controlled by a range of inherent factors (climate, depth, stoniness, mineralogy, texture) which interact to control plant productivity and rates of decomposition.
- Quantitative evidence linking soil OM levels and impacts on soil properties or crop yield is sparse and there is no critical or threshold value(s) identified for UK agricultural soils. However, in an unfertilized soil, where the role of soil OM cannot be masked by increasing application of fertiliser, there may be a critical level of OM needed to sustain crop yield.
- The review in Defra project SP0306 indicated that there may be some evidence that, if such a threshold or thresholds exist, then it or they would be nearer to 1 % soil organic C (1.7 % OM) than the level of 2% currently used as a rule of thumb.
- No critical or threshold values can be identified for labile OM, soil microbial biomass or any other soil biological parameters according to soil type, climate or farming system.

Impacts of farm management practices on soil life

- Farm management practices influence soil organisms both directly (through physiological effects on populations) and indirectly through impacts on soil habitats and/or other organisms.
- Modifications in inputs of OM to soil either through crop choice, rotation or amendment therefore have the largest potential impacts on soil organisms.
- Tillage which intentionally manipulates soil structure also has major impacts.
- Impacts of increased grazing intensity are mainly mediated through a series of complex interactions between changes in amount and quality of C inputs and modification to soil structure by compaction.

- Other amendments to soil (fertiliser, herbicides, pesticides, lime etc) have far smaller impacts
- While qualitative understanding of the impacts of single farm management practices is largely in place, there is a lack of quantitative understanding of the interacting impacts of farm management in practice.
- The research is not in place to underpin advice to farmers which would enable them to manipulate the rate or activity of any groups of soil organisms beneficially in a cost effective way – except for inoculation with rhizobia and for some biocontrol measures under controlled conditions.

3 Review of evidence

a. Roles of organic matter and soil life

Soils form as a result of the physical and chemical alteration (weathering) of parent materials (solid rocks and drift deposits). However, it is the incorporation of organic matter (OM) added as a result of the biological cycles of growth and decay that distinguishes soil from weathered rocks. In mineral soils in the UK, soils commonly contain 1 – 6 % of OM by mass consisting of plant, animal and microbial residues in various stages of decay. The OM content of soils is controlled by the balance between inputs of OM and rates of decomposition by soil organisms. In waterlogged conditions, decomposition of OM is slowed and OM contents can increase significantly leading eventually to peat formation. OM accumulation is also favoured by low temperatures and acidic conditions (low pH). Where soils are relatively undisturbed by man, the soil surface is often characterised by a layer of plant litter with organic matter incorporated into lower mineral horizons through the activity of soil organisms; OM content usually declines rapidly down the profile. Much OM in soil is inert or at least relatively inactive, contributing little to the behaviour of soil.A number of conceptual models have been used to divide the total OM in soil into pools/fractions where the most important distinction is between “old” and “young”/“active” fractions of OM (labile OM) such as polysaccharides, gums, fungal components of various kinds, root and/or microbial exudates, physical fractions and the readily decomposed components of manures, crop residues, slurries, etc..

In agricultural soils, OM affects a range of soil properties and processes that affect crop growth - improved plant nutrition (nitrogen, phosphorus, sulphur, micronutrients), ease of cultivation, penetration and seed-bed preparation, greater aggregate stability, lower bulk density, improved water holding capacity at low suctions, enhanced porosity and earlier warming in spring have all been observed (reviewed in Defra project SP0306). Many of these properties are clearly linked. However, while qualitative relationships have regularly been observed there are few quantitative links which allow soil OM contents to be used to predict these soil properties or crop growth (reviewed in Defra project SP0306). That review of the literature strongly implies that total OM in soil may be a poor guide to its function as a source of plant nutrition and of soil physical properties. It is labile OM that seems to be more important in affecting key soil properties. For example a decrease in total soil OM may be matched by an improvement in soil structure because the remaining OM, although small in amount, is composed almost entirely of labile OM. Under arable cropping, annual returns of crop residues to the soil are the major source of these active substances, whereas in grassland they are produced almost continuously by root exudation and turnover. This is likely to be the reason for better soil physical properties, especially aggregate stability, under grassland compared with arable soils.

The soil is home to organisms of all shapes and sizes (Figure 3.1; Table 3.1) making up 1-5% of total soil OM. The large majority of bacteria and fungi existing in soil (> 95%) are not culturable and so for a long time could not be studied; new molecular approaches are now revealing the genetic fingerprints of previously unknown organisms (Stockdale and Brookes, 2006). Much of our current understanding of the roles of bacteria and fungi in soil therefore derives from approaches which treat micro-organisms in soil as a single unit (the soil microbial biomass; Stockdale and Brookes, 2006).

Figure 3.1: Size grouping of soil organisms.

Bacteria and archaea, including free-living and symbiotic "species" Fungi including non-mycorrhizal and mycorrhizal species	Microorganisms
Protozoa Nematodes	Microfauna < 200 µm in diameter
Mites Collembola Enchytraeids	Mesofauna 100 µm – 2 mm in diameter
Earthworms Insects and other arthropods	Macrofauna >2mm in diameter

The architecture of the soil pore network makes up the habitat space in soil (Young and Ritz, 2000). It controls the balance of oxygen and water available to organisms at any given soil moisture potential, as well as regulating access of soil organisms to one another and to their resources. The amount and nature of the pore space in soil is dependent on soil texture and also on the formation and stabilisation of soil structure. Plant roots have a central role in structure development processes (Angers and Caron 1998). Grouping of soil organisms by size has been shown to be meaningful (Figure 3.1) as it allows a consideration of soil organisms in relation to the pore space within soils; larger organisms have restricted access to much of the soil pore space. However, soil organisms not only occupy soil; they are a living part of it and as a result of their interacting activities also change it (Killham 1994). Many soil organisms have key roles in the formation and stabilisation of soil structure (Beare *et al.* 1995). Ecosystem engineers are those organisms that change the structure of soil by burrowing, transport of soil particles and hence create micro-habitats for other soil organisms (Jones *et al.* 1994); in temperate agro-ecosystems, earthworms are very dominant within this functional group.

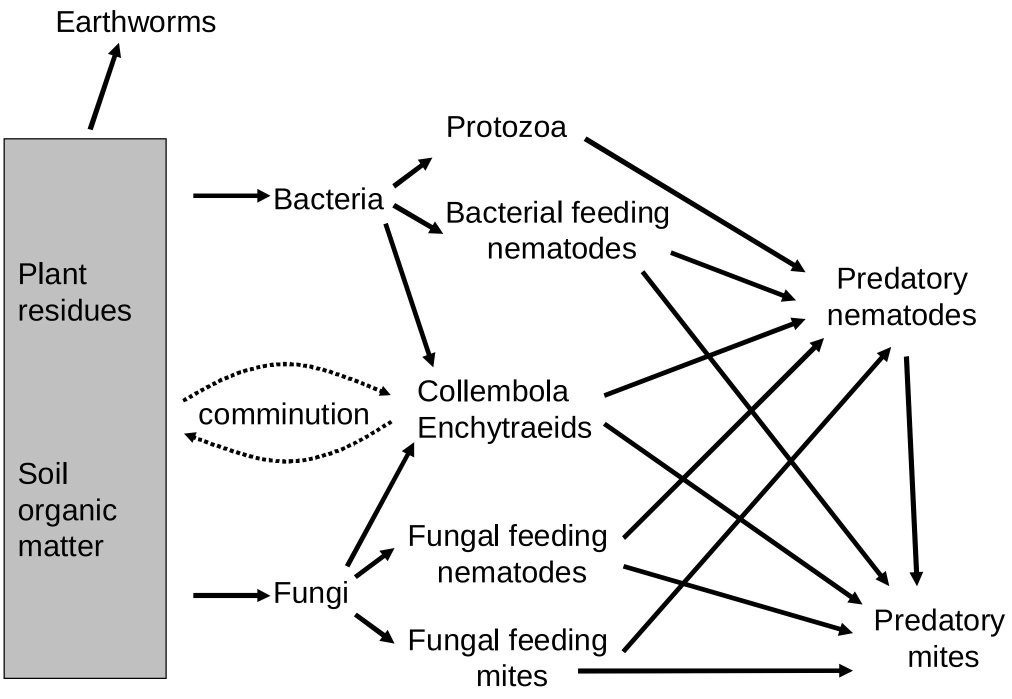
Table 3.2 Key groups of soil organisms and their main roles

Organism group	Main roles in soil
Bacteria	
Free-living	Decomposition and mineralisation of organic compounds (including agrochemicals and xenobiotics); synthesis of organic compounds (humus, antibiotics, gums); immobilisation of nutrients; mutualistic intestinal interactions; resource for grazing animals; formation of biofilms; pathogens of plants; parasites and pathogens of soil animals; helpers in mycorrhizal associations.
Symbionts	Some specialists identified by their particular role in soil processes e.g. methanotrophs, methylotrophs, methanogens, butyrate oxidisers, nitrifiers, denitrifiers, sulphur oxidisers, sulphate reducers, and many more. Association with plant species facilitating N_2-fixation; pathogens of plants; resource for grazing animals.

Fungi *Non-mycorrhizal*	Decomposition and mineralisation of organic compounds (including agrochemicals and xenobiotics); synthesis of organic compounds (humus, antibiotics, gums); immobilisation of nutrients; mutualistic and commensual associations; resource for grazing animals; parasites of nematodes and some insects; soil aggregation.
Mycorrhizal species	Mediation of the transport of water and ions from soil to plant roots; mediation of plant /plant exchanges of C and nutrients; regulation of water and ion movement through plants; regulation of photosynthetic rate; regulation of C allocation below-ground; protection from root disease and root herbivores; resource for grazing animals.
Protozoa	Grazers of bacteria and fungi; disperse bacteria and fungi; enhance nutrient availability; prey for nematodes and mesofauna; host for bacterial pathogens; parasites of higher-level organisms.
Nematodes	Grazers of bacteria and fungi; disperse bacteria and fungi; enhance nutrient availability; root herbivores; plant parasites; parasites and predators of micro-organisms, meso-organisms and insects;prey for meso- and macro-fauna.
Mites	Grazers of bacteria and fungi; consumption and comminution of plant litter and animal carcases; predators of nematodes and insects;root herbivores;disperse bacteria and fungi; host for range of parasites; disperse parasites, especially nematodes; parasites and parasitoids of insects and other arthopods; prey for macrofauna; modify soil structure at micro-scales.
Collembola (springtails)	Grazing of microorganisms and microfauna, especially in the rhizosphere; consumption and comminution of plant litter and animal carcases; micropredators of nematodes and other insects; disperse bacteria and fungi; host for range of parasites; disperse parasites, especially nematodes; prey for macrofauna; modify soil structure at micro-scales by production of faecal pellets.
Enchytraeids	Comminution of plant litter; grazing and dispersal of micro-organisms; create pores for movement; mix soil particles and organic matter.
Soil dwelling insects and other arthropods	Consumption and comminution of plant and animal matter; root herbivory modifying plant performance above and below-ground; grazing of microorganisms and microfauna; especially in the rhizosphere; dispersal of microorganisms; predators of other soil organisms.
Earthworms	Create pores in soil for movement; mix soil particles and organic matter; enhance microbial growth in gut; disperse microorganisms and algae; host to protozoan and other parasites.

A limited number of soil micro-organisms are able to obtain energy directly from light (photo-autotrophs) or as a result of chemical oxidation (chemo-autotrophs). However, soil OM is the main food resource for soil organisms as most rely on decomposition of the complex organic materials which comprise the soil OM to obtain energy. Soil organisms possess the enzymatic capacity to breakdown virtually all organic compounds added to soil e.g. pesticides, including persistent xenobiotics and natural polyphenolic compounds. Across a range of climates and systems Wardle (1992) therefore showed a strong correlation between the total OM content of soil and the size of the soil microbial biomass population. Where species are grouped according to their diet (trophic categories) then the food web in soils can be meaningfully described (e.g. Hunt *et al.*, 1987; de Ruiter *et al.* 1993 - Figure 3.2) showing the important roles of many species in controlling decomposition and nutrient availability through mineralisation.

Figure 3.2: Decomposition of organic matter shown in relation to the taxa of the soil food web. Taxa are sub-divided into trophic groups where relevant. Returns to the pool of soil organic matter in excreta and/or on the death of organisms are not shown.



The importance of soil processes in providing the biophysical necessities for human life and/or making other contributions towards human welfare has been confirmed. The identification and definition of key soil functions recognises the role of ecosystems in providing services that are of value to society. 80-90% of all soil processes are now known to be microbiologically mediated (Nannipieri et al. 2002) and therefore result from the interaction of soil organisms and soil OM. In each case the defined soil function is the result of the interaction and/or integration of a number of soil processes and in many cases the same processes may be linked to a number of functions. The Soil Action Plan for England (Defra, 2004) has defined six key soil functions:

- Food and fibre production
- Environmental interaction (between soils, air and water)
- Support of ecological habitats and biodiversity
- Protection of cultural heritage
- Providing a platform for construction
- Providing raw materials

The interactions of soil OM and soil organisms are critical for food and fibre production particularly with regard to: nitrogen fixation; transmission and prevention of soil-borne crop disease; interactions with plant roots; decomposition of organic substrates; and the transformation of nitrogen, phosphorus and sulphur through direct and indirect microbial action. However, there is also need for a wider consideration of the impact of soil management in agriculture on a range of other functions, e.g. water quality, greenhouse gas balances and flood mitigation, in which soil microbial processes also have a key role. At the same time there have been concerns about the degradation of soils and declines in OM levels and biodiversity have been identified as threats (EU, 2002). Maintenance and management of soil quality has therefore moved up the policy agenda so that soil protection is explicitly recognised within Good Agricultural and Environmental Condition (GAEC) which is part of the Cross Compliance framework.

Soil OM

It is important to be aware that the terms soil OM and soil organic carbon are often used interchangeably. Carbon (C) is a key fraction of soil OM comprising approximately 58% of the soil OM (this is the conversion factor used in Defra project SP0306). Most methods determine soil organic C; results may be reported as soil OM.

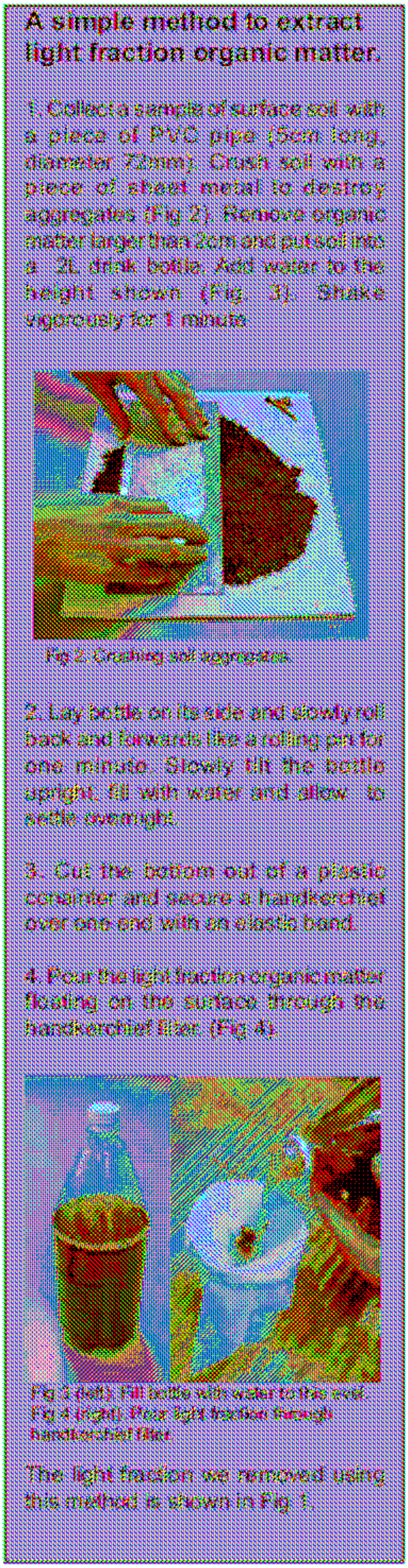
Routine analytical methods for soil OM include combustion and chemical oxidation methods (Table 3.3); all of these methods are used routinely in Europe (see survey associated with the research topic review: Laboratory mineral soil analysis and soil mineral management in organic farming). The Walkley-Black method, used since the 1930's, is a wet chemical oxidation which uses chromic acid as the oxidising agent; concern for the disposal of the chromium and the hazard of using this very strong acid by laboratory technicians means that this method is being increasingly replaced by automated combustion methods. However, care needs to be taken with interpreting results from combustion methods where soils contain a significant amount of calcium carbonate as this can also breakdown during combustion and hence affect the results. In soils of high pH (often pH > 7.5 is used as a threshold), separate determinations of the calcium carbonate content must be made and these data used to correct the results. Currently dry combustion at temperatures greater or equal to 900 ˚C is considered to give the most reliable determination of total soil OM measured as soil organic C, corrected for the presence of carbonate. However, Loss on Ignition measurements require only readily available equipment which is relatively inexpensive to purchase, operate, and maintain. Loss on ignition is often strongly correlated with soil organic C measured by dry combustion and may be sufficiently robust for on-farm monitoring.

Table 3.3 Common analysis methods for total and pools of soil OM.

Method type	*Comments*
Total organic C – dry combustion	High temperature combustion (> 900 ˚C); soil organic C calculated from determination of CO_2 released. Currently considered to be the most reliable method. e.g. Brye and Slaton (2003).
Total OM – loss on ignition	High temperature combustion (c. 400 ˚C); the weight loss is measured is proportional to the amount of SOM in the sample. Inaccurate for soils with low OM content, but shows good correlation to dry combustion. e.g. Konen et al. (2002)
OM and C measurements by combustion do not necessarily represent total organic C in areas where soils are calcareous. Must be corrected for CO_3^{2-} on all soils pH > 7.5	
Total organic carbon – chemical oxidation (modified Walkley Black)	Wet chemical oxidation with a titration step for analysis; time consuming and potentially hazardous method. e.g. Allison (1960)
Labile OM – Light fraction OM	Methods used in research e.g. Salas et al (2003).

or particulate OM	Approaches being taken to develop these methods and make them cost effective for routine use e.g.Defra project SP0310.
Labile OM – Permanaganate oxidation	Method developed in Australia (Blair et al. 1995) – used in monitoring in Western Australia (www.soilquality.com.au). Not working
Labile OM – Near Infrared Spectroscopy	Method under development, not yet in use routinely. May have problems with calibration as many soil components detected in a single analysis. REF

Methods determining labile soil OM often measure slightly different pools of OM, but which often show strong correlations (Table 3.3). Both light fraction OM and particulate OM are dominated by relatively fresh, undecomposed plant residues with a recognizable cellular structure. Particulate OM represents the 53–2,000 µm size fraction of soil OM that is not closely associated with soil minerals and is hence separated by sieving usually after soil dispersion; in contrast light fraction is obtained after soil dispersion by flotation (as OM is lighter than mineral material; Figure 3.3). In many instances these methods are not always clearly distinguishable and methods described in the literature as extracting particulate OM using a flotation step and vice versa. Neither approach is currently used in routine monitoring; however, Defra project OF0401 used this measure and showed differences between organic and conventional rotations which were related to the amounts of residues returned. None of these methods are routinely used in the UK or Europe for soil monitoring or agronomic advice.



A simple method to extract light fraction organic matter.

1. Collect a sample of surface soil with a piece of PVC pipe (5cm long, diameter 72mm). Crush soil with a piece of sheet metal to destroy aggregates (Fig 2). Remove organic matter larger than 2cm and put soil into a 2L drink bottle. Add water to the height shown (Fig. 3). Shake vigorously for 1 minute.

Fig 2. Crushing soil aggregates.

2. Lay bottle on its side and slowly roll back and forwards like a rolling pin for one minute. Slowly tilt the bottle upright, fill with water and allow to settle overnight.

3. Cut the bottom out of a plastic container and secure a handkerchief over one end with an elastic band.

4. Pour the light fraction organic matter floating on the surface through the handkerchief filter (Fig 4).

Fig 3 (left). Fill bottle with water to this level.
Fig 4 (right). Pour light fraction through handkerchief filter.

The light fraction we removed using this method is shown in Fig 1.

Figure 3.3

Example of a simplified method which can be used to study particulate/ light fraction OM.

Taken from the Soils are Alive Newsletter, University of Western Australia, 2000, Issue 4; available at soilhealth.com

Soil organisms

Measurements of soil organisms and/or other biological parameters are not routinely measured in the UK or elsewhere in Europe (see survey associated with the research topic review: Laboratory mineral soil analysis and soil mineral management in organic farming). Winder (2003) reviewed soil and environmental monitoring systems worldwide; the majority of soil monitoring programmes include measurements of soil nutrients, soil chemical properties e.g. pH, texture and heavy metal content; much less emphasis is currently placed on biological properties. Where biological properties are included these include estimates of the capacity of the soil to supply nutrients as a result of biological processes (mineralisable N; mineralisable C and enzyme activity) as well as measurements of the size of the soil microbial biomass and determination of some soil mesofaunal groups e.g. nematodes. Abbott and Murphy (2004) provided a comprehensive review of tests for biological components of soil (Table 3.4). Currently thirteen proposed biological indicators of soil quality (Defra project SP0529) are being tested in the field to identify those, if any, which are sufficiently robust for inclusion in a UK soil monitoring programme (Defra project SP0534). These are largely based on genetic profiling following extraction of DNA from soil, but also include the determination of the size of the soil microbial biomass and the diversity and size of the soil nematode and invertebrate communities.

Table 3.4 Examples of tests for biological components of soil with comments about the methodology; adapted with permission from Abbott and Murphy (2004). Methods can be by observation (i.e. direct) or by inference (indirect) based on assessment of products of reactions or other functional attributes.

MICROBIAL BIOMASS MEASUREMENTS	*Organisms can be assessed without first separating them into specific groups, but the identity of individuals making up the microbial biomass is not determined by these methods.*
Bacterial counts	Direct - It is possible to estimate the number of bacteria in soil, but this is a very rough estimate. An early method for estimating the size of the bacterial population. Completely accurate counts were soon realized to be impossible due to difficulties in distinguishing living and dead cells and due to close associations between bacterial colonies, clay surfaces and organic matter (Stockdale and Brookes, 2006). Calibration almost impossible. This method is too rough to use for reliable monitoring. Indirect - Although many soil bacteria will grow on agar or in nutrient broth, only a small proportion can do so, therefore indirect counts of bacteria based on this type of methodology are of little relevance to the number of bacteria in soil.
Fungal counts	Direct - Measurement of length of hyphae (km per g soil) is possible but it is not usually possible to identify the fungi present. Calibration almost impossible. Indirect - Some fungi can be grown on artificial nutrient media but this represents only 1-5% of the total organisms present. Therefore indirect counts of fungi based on this type of methodology are of little relevance to the study of fungi in soil. Quantification of some important fungal pathogens is possible in this way.
Total Soil Microbial Biomass (or microbial C, N, P, S etc)	Single methods can be used to measure the total size of the whole microbial biomass in soil – considered as a single entity. If roots and larger animals are removed from the soil prior to assessment, microbial biomass includes mainly microorganisms

	and smaller soil fauna (e.g. mites and springtails).
Fumigation-incubation	Fumigation methods involve killing the microbial biomass (or a large proportion of it) and then measuring the flush of nutrients (carbon or nitrogen) associated with its subsequent decomposition (Jenkinson and Powlson, 1976)
Substrate-induced respiration	Anderson and Domsch (1978) showed that short-term substrate-induced (glucose) maximal respiratory responses were correlated with actual, living total microbial biomass. However, this relies on stimulation with a single simple substrate and hence is not a reliable estimate of the whole microbial biomass.
Fumigation-extraction	This suite of methods has largely superceded the fumigation-incubation assays as they are simpler to carry out and more precise. Estimates of microbial biomass are determined using efficient constants (Jenkinson et al. 2004). Methodological problems associated with applying these methods to different soil types and at different times of the year have been extensively researched and the practical aspects are well understood. This methodology allows estimation of the amount of carbon, nitrogen, sulphur, or phosphorus associated with the soil microbial biomass.
ASSESSMENT OF GROUPS OF ORGANISMS	*Organisms in soil can be assessed in groups (e.g. mites or earthworms can be counted) or as number per group (e.g. as genera or species). For bacteria and fungi, special techniques can be used for particular groups: e.g. serological tests or molecular tests are available for some bacteria (e.g. rhizobia).*
Rhizobia	Direct - Isolation and identification is possible from soil or from nodules on field plants Indirect - Isolation and identification from plant bioassays; DNA probes are available for some species
Arbuscular mycorrhizal fungi	Direct - Arbuscular mycorrhizal fungi can be assessed by directly scoring colonisation of roots using a microscope. This is a tedious method and misses assign ? numbers of dormant fungi in soil Indirect - Bioassays using a standard bait plant can detect infective hyphae present in the soil at a particular point in time. DNA probes are beginning to be developed to allow assessment.
Protozoa	Direct - This is a tedious method. The total number is deceiving because it reflects multiplication (which depends on the availability of food such as bacteria) and predation (i.e. they are eaten by larger organisms)
Nematodes	Direct - Important for assessing presence of excessive numbers of plant pathogenic nematodes. Balance between beneficial and detrimental nematodes and different trophic groups can indicate food web structure. Indirect - DNA probes are available for some nematodes
Termites	Direct - Easily quantified and could be an indicator of soil health in some agricultural environments if calibrated
Enchytraeids	Direct -Could be an indicator of soil health in some agricultural environments if calibrated
Earthworms	Direct - Could be an indicator of soil health, but this is disputed

	because species differ between soils. Can be calibrated locally.
Microarthropods	Direct - Counts can be included in diversity indices
Plant pathogens	Direct - Root or leaf disease assessments Indirect - Molecular markers can be applied directly to soil or plants for some pathogens Indirect - Plant bioassays are easy to establish for some pathogens Tests can be calibrated as indicators of potential for plant disease (e.g. DNA tests, bioassays, root scores, disease rating)
SOIL BIODIVERSITY	*Expanding opportunities are being made available for measurement of soil biodiversity following extraction of DNA from soil, especially with the development of molecular tools. Caution is still required in interpreting the data from these methods.*
Responses to added substrates – community level physiological profiling	Indirect - This assesses the response of different components of the microbial community but caution is required in their interpretation.
Fatty acids (PLFA)	Indirect - Extracts a fraction of cell components which can be used to identify species to give a full biological fingerprint. Link to soil function not yet fully established; value for monitoring currently unclear.
Molecular methods (e.g. ARISA, TRFLP)	Indirect - Diversity in the DNA of the microbial population in soil reflects genetic diversity, but a link to soil function not yet fully established; value for monitoring unclear
MICROBIAL PROCESSES	*Quantification of biological processes can give an indication of the activity of soil organisms. This may be more relevant than the abundance of organisms for some purposes, therefore both abundance and activity measurements of soil organisms may be required*
Enzyme activity	Indirect – enzymes linked to a range of soil biogeochemical cycles e.g. carbon, sulphur, phosphorus, nitrogen can be assessed. e.g. cellulase activity can be assessed indirectly using the cotton strip assay or by biochemical means
Basal rates of respiration and/or mineralisation	Indirect - Incubation under optimum conditions of temperature and moisture and determination of carbon dioxide or mineral nitrogen released by mineralisation. Can be used as an indicator of microbial activity potential and give a respiration per unit of microbial biomass (respiratory quotient).
Substrate Induced Respiration (SIR)	Indirect - The 'potential activity' of soil organisms can be assessed by adding a relatively easily used carbon source (a sugar) and the amount of carbon dioxide released is measured. However, as soil organisms are adapted to a low carbon environment, its value is unclear. The complexity of the assay can be increased by using a range of substrates. However, this has largely been replaced by community level physiological profiling outlined above.
Nitrification	Indirect – Requires supply of a substrate and consequently any assay must be short to prevent adaptation of the microbial population.

Denitrification	Indirect – Requires supply of a substrate and usually assayed under conditions optimum for the process i.e. anaerobic and the assay must be short to prevent changes in the microbial population.
FUNGAL/BACTERIAL RATIOS	*Some management practices can change the relative abundance of fungi and bacteria in soil, so there is potential to use this as an indication of the impact of management practice on soil biological activity.*
Fungal bacterial ratio (direct count method)	Direct - Fungi and bacteria can be directly assessed (see above) and the ratio of their abundance calculated. However, the individual methods are unreliable and the ratio is not a useful indicator as it is too inaccurate when calculated in this way.
Fungal bacterial ratio (SIR method)	Indirect – This method assesses the ratio of fungi and bacteria in soil based on response to addition of carbon substrates (see SIR method above). It is based on inhibition of fungi and bacteria in separate assays and inhibition of all biological activity as a control which is difficult to achieve across different soils. However, the method is error prone, as inhibitors often don’t work
Fungal bacterial ratio (PLFA method)	Indirect - This method uses biochemical tests of fungi and bacteria (fatty acid analysis) as a basis for estimating the proportion of fungi and bacteria in soil (see above for fatty acids)

b. Interpretation of analysis data to guide management

While authors of reviews of soil biological fertility systems (e.g. Doran and Smith 1987; Beauchamp and Hume 1997; Clapperton *et al.* 2003) argue that maintenance and enhancement of soil biological fertility is of benefit within all agricultural systems, they provide no guidance on how soil analysis of any biological parameter could be used to support management decisions in practice.

Greenland *et al.* (1975) proposed a ‘*rule of thumb*’ that soils in England and Wales should be regarded as structurally unstable if the SOC content fell below 2%; equivalent to 3.4% soil OM. Despite intensive review (Defra projects SP0306, 0310, 0546) it has not been possible to verify this proposal or to identify clear thresholds for SOC/SOM in the UK. The maximum potential soil OM content at any site (Ingram and Fernandes 2001; Dick and Gregorich 2004) is thought to be controlled by a range of inherent factors (climate, depth, stoniness, mineralogy, texture) which interact to control plant productivity and rates of decomposition. Defra project 0310 established upper and lower limits of SOC that can be achieved through management according to the prevailing environmental and soil conditions in the UK assigning typical ranges for soil OM in arable soils according to clay content (5 groups) and rainfall (3 groups). However, quantitative evidence linking soil OM levels and impacts on soil properties or crop yield is sparse and the review in Defra project SP0306 has shown that there may be some evidence that, if such a threshold or thresholds exist, then it or they would be nearer to 1 per cent soil organic C (1.7 % OM) than Greenland’s rule of thumb. However, Defra project SP0306 concluded that in an unfertilized soil, where the role of soil OM cannot be masked by increasing application of fertiliser, there may be a critical level of OM needed to sustain crop yield. The potential importance of the level of labile organic C is not disputed, but insufficient quantitative evidence has yet been assembled to allow a critical level to be proposed. Without critical values then interpretation of data for any site can only be interpreted in relation to the long-term trend (analysis over 10-20 years) at the same site determined using a consistent sampling and analysis strategy. Such data are likely to exist for only a limited number of sites, largely associated with long-term experiments.

In relation to soil microbial biomass Lynch *et al.* (2004) cite two studies which suggest that there is a critical level of SOM for microbial functional diversity in soil (1.7% OM). Almost no work has been done to establish critical levels for soil microbial biomass or any other biological parameter. Because of the close relationship between soil OM contents and the size of the soil microbial biomass pool (Wardle 1992), it is not unreasonable to suggest that a similar range of site factors (climate, depth, stoniness, mineralogy, texture) might define the potential size of the below-ground biomass populations. However, quantitative evidence linking soil biological parameters and impacts on soil functions or crop yield is very sparse and there is currently no evidence of an appropriate threshold or range of threshold values for soil types, climates or farming systems.

c. Impacts of farm management practices on soil life

The inherent properties of any site have a major effect on soil organisms in terms of both the size and activity of their populations. Hence some sites will always have higher size, activity and diversity of soil organisms than others as a result of combination of these unmanageable fixed site factors. However, land management practices will also influence soil organisms both directly (through physiological effects on populations) and indirectly through impacts on soil habitats and/or other organisms. An extensive recent review (Stockdale et al 2006) of the impacts of farm management practices on below-ground biodiversity and ecosystem function concluded that very few agricultural management practices have simple and/or generalisable impacts.

The central role of decomposition and soil structural development and stabilisation processes in controlling the processes in soil which together support crop growth means that practices which impact on these interactions will have the largest effect on crop yield and soil function. Consequently modifications of the inputs of OM to soil either through crop choice, rotation or amendment therefore have the largest potential impacts. Tillage which intentionally manipulates soil structure also has major impacts. Impacts of increased grazing intensity are mainly mediated through a series of complex interactions between changes in amount and quality of C inputs and modification to soil structure by compaction. Other amendments to soil (fertiliser, herbicides, pesticides, lime etc) have far smaller impacts (Table 3.5).

Table 3.5 Summary of direct and indirect impacts of agricultural management practice on the soil population (adapted from Stockdale et al. 2006)

Practice	Direct impacts	Indirect impacts
Tillage	Kills soil macrofauna, earthworms and beetles	Destroys/ damages root systems Changes pore size distributions; and aerates in the cultivated layer Mixes organic residues and stimulates mineralisation
Rotation of a variety of crops		Increases diversity of inputs of OM in space and time Increased variety of nutrient uptake patterns Inclusion of deep rooting crops will increase larger pores at depth
Grass/clover mixture	Provides habitat for rhizobium population to develop	Reduces root biomass compared to grass only swards Changes residue quality, increasing readily decomposed material Legumes are more acidifying that grass as a result of ion balance during nutrient uptake
Crop residues	Rapid decomposition can control some pathogens	Stimulate/ reduce mineralization depending on carbon/nitrogen ratio Rapid decomposition can lead to development of anaerobic microsites Decomposition may stimulate aggregation
Increasing grazing intensity		Fertiliser effect of dung and urine effect stimulates growth and increased returns of OM Defoliation stimulates root exudation of readily degraded organic compounds Where compaction occurs, change pore size distribution leads to reduced infiltration and changes in root morphology
Herbicides		Kills roots and increases root turnover
Insecticide	Kills insects	Increases life of roots and may increase surface area
Fungicide	Cu-based fungicides accumulate and have toxic effects	Accumulation of Cu in soil to toxic levels where Cu-based fungicides used
Drainage	Installation kills larger organisms.	Increased rooting in drained soils Increased aeration, stimulation of nitrification

Practice	Direct impacts	Indirect impacts
Fertiliser	High soluble P restricts AM fungi	Increase surface area of roots Increases crop residue return Locally high short-term levels of nutrients May decrease pH (particularly NH_4, S-based fertilisers)
FYM		Returns of OM may stimulate/ reduce mineralisation depending on C:N ratio Fertiliser effect stimulates growth of roots Usually raises pH Increase nutrient availability. Medium term availability Stimulates structural formation processes after disturbance. Improve structural stability in some soils
Slurry	High NH_4 levels can control some pathogens	Fertiliser effect stimulates growth of roots and return of crop residues Increase N,P,K availability in short to medium term
Compost		Improved rooting distribution Usually little impact on mineralisation depending on C:N ratio Increase P, K availability Stimulates structural formation processes after disturbance. Tends to increase stability of transmission and structural pores and/or increase water holding capacity depending on soil type.
Sewage sludge	May be toxicity effect after number of applications	May be a fertiliser effect to stimulate growth and return of crop residues Possible toxicity of metals and persistent organics

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Differences in the quality as much as the quantity of organic matter input have a driving impact on the microbial community in soil and on decomposition and cycling of C and N. Plants are also the main point at which humans intervene in agro-ecosystems determining the species richness, genetic variability and organisation in space and time of crops, if not of weeds. Crop rotation and in-field crop diversity therefore has a major impact on soil organisms potentially providing them “a varied and balanced diet”. Impacts of OM inputs are modified by the impact of tillage and other residue management practice and the particular climate/soil conditions at any site (Doran and Smith 1987). Where plant communities are managed carefully (e.g. through return of residues, mulching etc) it has been shown that agricultural intensification does not adversely affect microbial and arthropod communities e.g. (Wardle et al. 1999, Yeates et al. 1999).

Taking AM fungi as an example (Table 3.6), reduced plant species diversity (and modern cultivars), the use of non-mycorrhizal crops, fallow and excessive tillage are all likely to contribute to a negative impact on mycorrhizal species diversity and infectivity. Rotational cropping using a range of appropriate hosts with reduced tillage intensity and regular inputs of OM is likely to be generally positive for AM fungi. Hence advice targeted at improving AM fungal populations would stress the positive and advise minimisation of the negative.

Table 3.6 Summary of impacts of agricultural practices on AM fungi (for more detail see Harrier and Watson 2003, Gosling et al. 2006).

Direction of effect	Practice
Positive	Rotations Weeds
Negative	Monoculture Non-host in rotation Bare fallow = no host Modern cultivars Intensive tillage Increased soil soluble P
Variable	Intercrops N fertilisation Organic amendments Biocides (herbicides, pesticides) Grazing

Similar tables of qualitative assesment might be compiled for other soil organisms, however, there are no specific and practical management steps identified for farmers even on a region by region or system by system basis which might allow the reliable manipulation of soil organisms through changes in agricultural practices. Some guidance where inoculants of N fixing bacteria or biocontrol agents are used to indicate practices that are likely to support their effectiveness and persistence. However, current advice to farmers that rhizobial survival in soils is increased where crop rotations include regular legume phases, soil pH is maintained in the neutral to slightly alkaline range and soil organic matter levels maintained or increased, can barely be distinguished from the more poetic injunctions of Burkett (1917): ‘If you would have such visitors remain with you always you must do your part in making their new home comfortable and satisfactory to them. …You must keep the soil free from stagnant water; keep it sweet …; keep it open and mellow and fine; keep it free and attractive to air and like wholesome influences’ (p. 143). Very occasionally proposals are made for the targeted and practical management of the soil food web. For example Ferris *et al.* (2004)

demonstrated in California how the combined use of use of irrigation and the provision of a carbon source (cover crops and straw incorporation) within a modified agricultural system could support the persistence of the nematode population through late summer in a Mediterranean climate was able to increase microbial activity and N availability into the following spring to the direct benefit of the subsequent summer tomato crop.

During the PACA Res Soil workshop (9.4.08) considerable discussion took place between advisers and researchers on the role, analysis and management of soil structure, minerals and biology, a summary of key additional points is provided in Appendix 2.

Why has the growth in understanding of role of soil OM and soil organisms, outlined briefly above, had such little impact on the practical management agricultural systems, even in organic farming where the importance of soil health is a particular focus? For farmers to take account of any process or species within the agricultural ecosystem, they must also be able to manipulate its rate or activity beneficially and such manipulation must be cost effective. Further innovative and collaborative research is needed by scientists, advisors and farmers not simply to increase understanding of the factors that affect soil organisms and their interaction with soil OM but also the development of targeted practical management approaches.

4. Acknowledgements

This review was sponsored by PacaRes: Providing Access, Collation and Analysis of Defra research in the organic sector. This project is managed by IOTA and funded by Defra and aims to improve the awareness and uptake of organic research by farmers.

We are also extremely grateful to colleagues who responded to the questionnaire: Harald Scmidt, Bernhard Freyer, Paul Maeder, Berner Alfred, Geert-Jan van der Burgt, Riekje Bruinenberg, Jurgen Friedel, Anne-Kristin Løes, Silvia Haneklaus, Carlo Grignani and Ingrid Oborn.

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Appendix 1:
Relevant Defra funded research

Understanding soil fertility in organically farmed systems - OF0164

Time-Scale and Cost

From: 1999

To: 2002

Cost: £325,851

Contractor / Funded Organisations

ADAS UK Ltd., Institute of Grassland and Environment Research (IGER), Henry Doubleday Research Association, University of Wales, Bangor

Executive summary of final report

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.

Changes to soil quality indicators following conversion to organic vegetable production - OF0401

Time-Scale and Cost

From: 2001

To: 2002

Cost: £62,706

Contractor / Funded Organisations

Horticulture Research International

Executive summary of final report

Increasing interest in low input agriculture together with growing environmental awareness, has led to recognition of the need to maintain and enhance soil resources. This has highlighted the requirement for a greater understanding of factors controlling soil 'quality' or 'health' attributes which contribute to sustainability. More reliable methods of assessment need to be developed, so that soil quality can be enhanced to improve productivity. This is particularly true in organic systems, in which fertility is promoted by the inclusion of fertility building crops within rotations, and by the incorporation of composted waste materials, in the absence of chemical fertilizer and pesticide inputs.

The aim of this 1 year study was to examine how key functional indicators of soil quality are affected by contrasting organic and conventional management regimes. In particular, the project investigated the impact of contrasting fertility building regimes on soil quality, focussing on the initial 5 year period following conversion from conventional to organic production. The study supports Defra's policy objectives of assessing and improving the sustainability of organic farming, including the impacts of organic farming on the soil environment, and on sustainability. Additionally, the study contributes to the development of reliable indicators of soil quality for research and monitoring purposes, addressing a need highlighted in the Draft Soil Strategy Document for England

The study site was located on the farm at HRI-Wellesbourne, and is part of a network of organic farms being monitored by HDRA for crop and economic performance as part of projects OF0126T and OF0191. Five 0.8 ha areas were selected for study. These were; two organic vegetable rotations supporting contrasting fertility building regimes, an organic arable rotation, a grass-clover ley and a conventionally managed cereal rotation. The organic areas were located in Hunts Mill field, which had been converted from conventional cereal production 5 years prior to the start of the study. The conventional area was located in Deep Slade field, which is adjacent to Hunts Mill. A range of chemical, biological and physical attributes were determined.

There were differences between the organic and conventional management regimes in most chemical, biological and physical soil quality parameters. Contrasting organic management regimes had different effects on soil quality. Relative to organic vegetable and conventional arable management, the organic arable management rotation enhanced amounts of light fraction organic matter and labile N, with beneficial implications for long term nutrient retention and soil organic matter development. There was little difference in chemical quality between the organic vegetable and the conventional arable areas.

There was evidence that organic management promoted a microbial community that was distinct in composition and functional attributes to that in conventional soil. Relative to conventional management, areas under organic management had greatly increased inoculum of arbuscular mycorrhizal fungi, a larger proportion of 'active' relative to 'resting' biomass within the microbiota, increased metabolic diversity and a distinct microbial community metabolism. However, there was evidence that the productivity of newly converted organic systems could be limited by low inoculum and diversity of arbuscular mycorrhizal fungi inherited following conventional management.

The clearest effect on soil structure was with regard to the detrimental effects of vegetable production rather than to any benefit associated with organic management. Wheeling lines caused compaction that resulted in poor growth of subsequent cereal crops. However, it is likely that increased levels of organic matter may result in a soil better able to cope with damaging operations.

There were differences in the susceptibility of the chemical and biological quality parameters to change. Different susceptibilities of quality parameters to change provides possibilities to use selected parameters as early indicators of the effects of management on soil quality. Furthermore, the results highlight the need to consider a wide variety of 'quality' analyses when investigating soil quality, since limited data sets focussing on traditional measures of soil quality (e.g. total SOM and biomass-N) are too rudimentary to pick up changes to soil functional attributes, and could lead to unsound conclusions regarding the effects of management on soil quality.

There are opportunities to conduct further statistical analysis of our comprehensive data set in order to develop an index suitable for quantifying soil quality in organic systems. Such an index would be of generic value to rate soil quality in diverse agricultural systems. Further work is needed to determine the applicability and conclusions of our study to other soil types and organic management regimes. The work has highlighted fundamental shifts in microbial community structure and functioning following conversion from conventional to organic management. There is a need to characterise and quantify these changes. This will provide new groups of 'indicator' organisms which could be suitable for assessing changes to soil quality, and could also provide opportunities to manage soil microbial communities to improve the sustainability of organic and conventional farming.

Critical levels of soil organic matter - SP0306

Time-Scale and Cost

From: 1997

To: 2000

Cost: £179,741

Contractor / Funded Organisations

Soil Survey and Land Research Centre, ADAS UK Ltd.

Executive summary of final report

It is widely known that amounts of a few per cent of soil organic matter (SOM) or soil organic carbon (SOC) confer desirable properties on many soils, e.g. better structure, better seed beds, improved water holding capacity, easier seed emergence, and so on. There has been increasing concern that increasingly intensive farming is causing the SOM contents of soils to fall to unacceptable levels. Again, there is a widespread belief that if SOM falls below a critical threshold, then there will be serious decline in crop yields, increased erosion, and general degradation of the soil resource sufficient to threaten the UK's ability to maintain acceptable levels of food production. There will also be environmental consequences of such degradation. The setting of such a critical threshold for all soils and land-use systems, or of different thresholds for different soils and land-use practices is a matter of much debate. A widely held view is that the lower limit for such a threshold should be 2 per cent organic carbon, which is equivalent, by convention, to c. 3.4 per cent organic matter.

This research has examined the evidence for such a threshold or thresholds. It set out to do this from a firm quantitative, i.e. numerical, standpoint. Anecdote was viewed as insufficient evidence. The requirement was for equations of state, properly replicated experiments with adequate statistical treatment, and evidence of wide applicability of the findings.

Approximately 1200 published papers and reports were examined initially - mostly in relation to temperate soils, in order to assess the opinions in the literature. This search revealed a surprisingly small number of published works which contained data and interpretations meeting the requirement for numerical robustness. There was limited evidence that a decline of c. 5 per cent might occur in cereal yields if SOC contents approached 1 per cent, and that this decline could not be corrected by the addition of greater amounts of inorganic N, P and K fertilisers. One or two papers suggested that soil structure - as measured by aggregate stability - would deteriorate to unacceptable levels if SOC approached 2 per cent. Such evidence as was found was often conflicting, e.g. some work showed marked change in soil properties above or below a particular threshold of SOM or SOC, whilst similar work from other groups failed to confirm such findings. There was almost no evidence from the literature that *thresholds* - if they existed - differed significantly between soil types, even though the amounts of SOC are known to differ between, for example, soil textural groups.

Investigation of data sets from England and Wales showed that SOC explained c. 10 per cent of the variation in the water holding capacity of topsoils, and that this contribution varied relatively little between soil types and land uses. SOC makes almost no contribution to the water holding capacity of subsoils. In terms of soil structure - as expressed by dispersibility of soil aggregates - there is a marked decrease in stability of a wide range of soils under arable cultivation below c. 1.5 per cent SOC. Soil organic carbon makes relatively little contribution to the plastic behaviour of agricultural soils in England and Wales, i.e. how readily they deform, and none at all to soil liquid limit, i.e. the point above which soils lose all mechanical strength. SOM can be a considerable source of plant nutrients, especially nitrogen (N). Work on sandy, clayey and chalk soils indicated a linear relationship between potentially soil mineralisable N (PMN) and SOC, but with no marked cut-offs. Sandy soils tend to contain less SOC so, as would be expected, they yield less PMN; usually <100kg N ha^{-1} yr^{-1}. Chalk soils occupy an intermediate position, releasing roughly 100 - 150 kg N ha^{-1} yr^{-1}, whilst clayey soils can release almost 400 kg N ha^{-1} yr^{-1} - although 150 - 250 is more usual.

Mathematical modelling of SOC behaviour used the ROTH-C model from IACR-Rothamsted, and the CENTURY model, from N. America. Although both gave comparable results on sets of test data, CENTURY over-estimated SOC contents to a greater extent than ROTH-C. Further, ROTH-C was found easier to use with SSLRC data, and as help with the model was readily available in the UK, further modelling was confined to ROTH-C. The modelling showed that soils with <18 per cent clay, and chalk soils, tended to an equilibrium SOC concentration of c. 1.3 per cent over periods of 100 years or more of continuous arable production. Soils with >18 per cent clay tended to an equilibrium value of c. 2.3 per cent SOC. These equilibrium values were independent of varying N inputs. Application of the medium-high climate change scenario (UK Climate Impacts Programme) as the climate input to ROTH-C caused these equilibrium SOC contents to decline further by c. 0.5 per cent. It should be realised, however, that the modelling and the assessment of the output from it depends on the interpretation of changes in SOC that are small. There are many uncertainties in this, so the interpretations should be treated with due caution. It should also be noted that the modelling assumed only one kind of land use over these long periods of time. This is unlikely in practice, so the results of the modelling could be regarded as 'worst-case' scenarios.

The lack of clear thresholds for SOC/SOM in relation to soil properties, either from the literature, or from this work, made the derivation and application of SOC-related risk assessments difficult. However, by comparing the modelled data with the National Soil Inventory data, it can be seen that significant areas of Eastern England could suffer falls in SOC under long-term arable cultivation. The loss of SOC is unlikely to be made good by current returns of SOC from crop residues from arable agriculture. It seems, however, that the heavier soils, even though many of them have quite small SOC contents - 2 to 3 per cent is common, will remain at about these values provided that current crop residue returns do not decline. Clearly, however, the effect of climate change could alter both these positions.

Few data exist for crop returns under long-term managed grass. Modelling with these data indicated that SOC contents of permanent grass soils will increase in all soils in the long-term. This conflicts with the findings of the recent re-sampling of NSI sites, which showed that SOC contents in permanent grass soils were declining slightly after only c. 15 years. However, we found that the 'balance-point' between SOC increase or decline was very close to the currently assumed values of SOC inputs under grass (c. 2.8 t C ha^{-1} yr^{-1} for the latter, compared to c. 2.6 t C ha^{-1} yr^{-1} for the former). It remains a question, therefore, how representative the current permanent grass data are for large areas of the country. If this aspect is to be investigated further, then clearly a wider range of SOC input values under grass is required.

There are many papers in the literature which give better relationships between soil properties and 'active SOM', i.e. the relatively short-lived components of manures, crop residues, slurries and so on. We were unable to assess the importance of these 'active carbon' yr^{-1} in the soils of England and Wales because there are almost no data. This is clearly also an area for further research.

In conclusion, we found little clear evidence for critical thresholds of SOC in the soils of England and Wales. If such a value or values can be demonstrated, it - or they - might lie closer to 1 per cent SOC than the widely-proposed figure of 2 per cent. It might be that 2 per cent or more of SOC is seen as desirable from a precautionary point of view, but the *quantitative* evidence to support this is weak.

To develop a robust indicator of soil organic matter status - SP0310

Time-Scale and Cost

From: 2001

To: 2004

Cost: £395,576

Contractor / Funded Organisations

Rothamsted Research (BBSRC)

Executive summary of final report

In this project we found, using information provided by farmers, that typically there was financial benefit to be gained from improved management of soil organic matter (SOM) in the arable and mixed farming enterprises of England and Wales. The extent of this potential benefit was influenced by characteristics of the enterprise and environmental situation (“physiotope”) as well as management history. In many cases the farmers interviewed were not able to assess the financial costs and benefits of managing organic matter in their soils, and a number only recognised benefits of organic matter management upon prompting.

We consider it unlikely that the level of financial return which may be expected can be explicitly linked to a single soil measurement but our findings suggest that in conjunction with a preliminary assessment of soil organic carbon (SOC) status, simple underlying rules could be established that enable the potential for benefit (and/or risk) associated with change in organic matter management to be assessed.

We established a framework by which SOC status may be assessed using tools to

(i) compare the SOC content of a particular soil against statistically derived (“manageable”) ranges for the relevant physiotope, and

(ii) detect an effect of altered management practice before they can be measured in total SOC by measuring an active fraction of SOC.

A key further step will be to find ways to use these simple readily-understandable tools to identify opportunities for increased financial return through changes in organic matter management.

The cost–benefit data that we collected from farms, where available, showed that the mean net return to managing soil organic matter was between £31 ha^{-1} (lower bound) and £66 ha^{-1} (upper bound). The lower bound applies when (in mixed farming systems) the high costs of incorporating FYM or slurry (muck) are included, and the upper where these costs are attributed to the associated livestock business. Using the lower bound 15 % of farms experienced negative net returns to SOM management; applying the upper bound, none did. Calculating the internal rate of return to SOM management, accounting for the time taken for the benefits to accrue (typically one to two years for mixed farms and five years for arable) we found a median figure of 52 % (based on the lower bound net value). The typically high rate of return indicates that whilst the financial benefits are fairly modest in absolute terms they are often significantly higher than the costs involved. Further, the net returns are significantly higher where farmers apply their efforts to high value crops. We also noted that the returns were significantly lower where the existing demand for (and hence price of) straw was relatively high. The few farms managing SOM using biosolids (available free) were obtaining a higher net financial return than those relying only on straw or muck. Those farms incorporating both straw and muck appeared to get the highest net return. The net financial benefit did not vary significantly with any of the methods of valuation we have used – detailed versus partial cost–benefit data, or an estimate of the farmers "willingness to pay". Further, farm size and the position of soil C content within its manageable range did not appear to affect financial return.

The "manageable" SOC ranges applying to a particular site (arable or ley–arable land-use) were defined using the large SOC dataset of the National Soils Inventory (NSI). After excluding sites susceptible to flooding or displaying calcareous surface horizons or high pH we could assign 25.5 % of total variation in SOC between sites to a combination of soil clay content and average annual precipitation. Lower and upper limits to SOC were statistically defined for 15 combinations of clay content (five classes) and rainfall (three classes) as the 80 % confidence intervals of the *Qn* statistic around the median. We found that straightforward reports that indicated the position of a soil within the range applicable to its physiotope offered a simple and effective means to communicate the manageable range concept to farmers participating in the study.

Our indicator of active C was developed, and its ability to determine whether SOC was accumulating or declining in a particular soil through a one-time measurement tested. The active C fraction corresponds to the intra-aggregate light fraction isolated by an existing separation procedure developed at Rothamsted, shown in earlier work to represent material in transition between fresh and stabilised C, and with a turnover time of 2 to 10 years. We scaled up the existing procedure to provide a faster measurement at lower cost from larger samples of heterogeneous (field) soils. We conducted preliminary tests that might reduce the cost of the measurement cost (£47 to £67 per field) by a further 30 % by refining the rapid, low-cost (gravimetric) method for estimating C content tested in this project. Using measurements of active C from approx. 30 farm and experimental field soils we defined a statistical relationship (bound by 95 % confidence limits) between active C and clay content for fields categorised as "stable" in their SOC content. In our test of the indicator, we found that 70 % of cases could expectedly be defined as "unstable" in SOC when compared against these limits.

Soil Organic matter as a headline indicator of soil health - SP0546

Time-Scale and Cost
From: 2004

To: 2005

Cost: £51,350

Contractor / Funded Organisations
University - Cranfield

Executive summary of final report
Soil organic matter (SOM) has been chosen as the headline indicator of soil health for the "Sustainable Farming and Food Strategy" within Defra. The derivation of a robust indicator of SOM will help show whether there has been a halt the decline of soil organic matter caused by agricultural practices in vulnerable soils, and whether the SOM content of other agricultural soils has been maintained, whilst taking into account the impacts of climate change. The need for two groups of vulnerable soils with respect to SOM is identified. These groups are firstly those already at or below a lower threshold and secondly those above the threshold but which are showing a greater than average rate of loss. The policy, management and monitoring implications of these groups are different, for example SOM in the low SOM soils could be addressed through measures such as Good Agricultural and Environmental Condition (GAEC) as part of Cross Compliance, whereas those showing higher rates of loss may be driven by climate change and land management in upland areas.

The agricultural sites visited during the re-sampling of the NSI were grouped into the appropriate physiotope, and then the median and 10th percentile values for soil organic carbon (SOC) calculated. 1980 has been used as the baseline year and the 10th. percentile as the lower threshold. This lower threshold does not necessarily reflect changes in soil functions and is used only to assess relative numbers of sites that have SOC contents greater or less than the value and should only be used with care. Although many studies have demonstrated numerical relationships between SOC and various soil properties, firm evidence of a threshold above or below which the contribution of carbon increases or decreases significantly is rare.

- The overall conclusion is that sites in arable cultivation and rotational and permanent grassland re-sampled between 1995 and 1997 showed a slight (but not significant) increase in the number of soils below the threshold.
- The analysis of the data by individual physiotope confirmed earlier findings that more re-sampled soils with greater than 18% clay were below the 1980 threshold than those with less than 18% clay. As annual rainfall increased so did the proportion of soils under arable and rotational grass below the threshold suggesting a possible link to loss of dissolved organic carbon or changes in moisture status as a result of climate change.
- The extensively managed sites showed varying changes in the number of vulnerable sites, for example, bog, upland heath and upland grass showed a large increase whereas coniferous woodland showed a decrease. The result of the analysis by soil type is that peat soils followed by lithomorphic (shallow) soils are the most vulnerable in terms of rate of loss of SOC over time.

- The most vulnerable land use to loss of SOC is bog followed by upland heath/grass/moor. Arable and permanent and rotational grass sites are losing SOC at only half the relative rate of bogs but, significantly, grassland sites are as vulnerable as arable sites.
- The most vulnerable soils across all land use groups are those with a high SOC in the 1980s. Those with very low baseline contents (less than 20 g/kg) are slightly increasing in SOC in both relative and absolute terms.

The use of Soilscapes is suggested as a means of identifying the spatial extent of vulnerable soils. The trends identified and their relation to the Soilscape should be viewed as summaries only. The analysis does not suggest that all the soils in a particular landscape are vulnerable, more that if resources are to be targeted by soil type then those with high rates of loss and/or with more soils below the 1980 threshold should be a priority.

- Soilscapes with sites in arable cultivation with a higher than average loss rate of SOC are “Loamy and sandy soils with naturally high groundwater and a peaty surface in arable cultivation”.
- There are no Soilscapes with sites in permanent grassland with a higher than average loss rate of SOC.
- Soilscapes with sites in extensive management with a higher than average loss rate of SOC are: “Very acid loamy upland soils with a wet peaty surface“ (upland grazing), “Slowly permeable wet very acid upland soils with a peaty surface“ (upland heath, rough grazing, upland grazing, coniferous woodland) and “Blanket bog peat soils“ (bog).
- Soilscapes that show an increase in the number of soils below the 1980 threshold under arable cultivation are: “Freely draining lime-rich loamy soils“, “Freely draining slightly acid but base-rich soils“, “Naturally wet very acid sandy and loamy soils“ and “Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils“.
- Soilscapes that show an increase in the number of soils below the 1980 threshold under permanent grassland are: “Shallow lime-rich soils over chalk or limestone“, “Freely draining slightly acid loamy soils“, “Slightly acid loamy and clayey soils with impeded drainage“ and “Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils“.

Thirty sites in arable cultivation at which the management had been recorded over the years were sampled. The trend in the relationship between first measured SOC and rate of change was similar to that identified in other studies. However, there are no soil drivers evident when the rate of change in SOC was plotted against the clay content i.e. rate of change does not change above and below 18%. There is no distinctive land or crop management, for example depth of cultivation, or soil differences, which could be identified as a driver. There are many examples of how indicators of soil health, sub-ordinate (at least partially) to SOM, relate to differing treatments and impositions on soil. They are a valuable insight into how individual soils and sites react, but few even attempt to make quantitative links between indicators. This is partly due to the complex relationships between them, and often unspecified outside management factors, as well as the individual nature of inter-site variation. Nevertheless if indicators are to have any value in a monitoring programme then they have to show at least a minimum change in value that has some meaning in terms of soil health. Often this may be in relation to another indicator and a final result that signifies soil damage of some form. This is particularly pertinent to the chosen headline indicator of SOM, which may exhibit quite a high degree of variation before any changes in other soil properties are measurable.

The report concludes that further work is required on the issue of a switch from a carbon to phosphorus economy if agriculture is to be re-based in nutrient-balancing systems. This is crucial if the concept of vulnerable zones is extended from nitrogen to, for example, P (and C). However, targeting increases in SOC may have implications for other nutrient balances. For example there are constraints on the amounts of N that can be added as manure or sludge in Nitrate Vulnerable Zones to the soils that are lowest in SOC. Increasingly P applications are being monitored and release to water courses controlled by buffer strips. Following the analysis to identify vulnerable soils in respect of their relation to a threshold value or the rate at which the SOC content is changing, their optimal management depends on what outcome is required for example, carbon sequestration and/or CO2 reduction, whether management and/or land use change is an option and finally which policy drivers can be enacted to achieve these aims. Assuming no changes in the land management, then the NSI and Century modelling of the impacts of climate change suggest that the SOC in arable topsoils will stabilise and that permanent grassland topsoils will continue to loose SOC to 2040 and then stabilise. Changes in the SOC component after a land management change are only minor contributions in relation to virtually all other changes – amounting to only 1.27 MtC within a total of 31.44 MtC over 25 years for arable conditions in England. Changes in arable management could make a significant contribution to an abatement strategy if carried out in concert, with the greater use of permanent conservation field margins, increased returns of crop residues and reduced tillage systems, contributing 1.3 Mt C per year in the initial years. It should be noted however, that true soil carbon sequestration would be only a minor component of this (125 kt C per year), the main part being savings on CO2 emissions from reduced energy use, and lower N2O emissions from reduced use of inorganic nitrogen fertiliser. A large contribution could be made, however, from simply ensuring that all cereal straw residues are returned to the land either as straw or farmyard manure. This could be cost effective, though requiring an extra financial incentive to promote it.

The conclusion is that the potential for genuine carbon sequestration to soil by agricultural management changes is very limited under English conditions. In some cases sequestration and savings can be negated over time by changes in the emission of other greenhouse gases and energy use. It is also clear that large savings in the national inventory of greenhouse gas emissions will only come from wholesale land use change as single measures (to woodland, energy crops and a return to temporary grass leys in arable rotations). However, some of the arable management changes are not mutually exclusive, and could be run together. A scenario whereby tillage was universally by minimum methods, all straw returned and 6 m permanent “set-aside” margins employed, would give a combined sequestration/saving potential of 31 Mt C (115 Mt CO2 emissions) over 25 years. This is comparable to increasing the woodland component of the landscape by about 3%, and more than the contribution envisaged from soil sequestration and saving due to energy crops (not including that due to their energy production). It would however, involve about a 7% drop in agricultural production and require a considerable financial incentive to overcome the loss sustained by farmers. Measures under Cross Compliance and the Entry Level Agri-environment Scheme to reduce erosion will contribute indirectly by stabilising sandy and light loamy soils through grass strips, beetle banks and stubble maintenance. There are no direct measures for maintaining SOC in grassland soils but measures aimed at reducing stocking density will help. It should not be assumed that grassland soils store SOC, the intensity of management and climate are important factors which can change such soils from sinks to sources. An important dimension to any monitoring scheme must be that the results should be able to reflect whether English farmers are maintaining SOM at 1990 levels as required by the Cross Compliance regulations. The main concern is with the land under semi-natural grassland and other non-agricultural management, although deciduous and coniferous woodland soils show low rates of loss. Highest rates of loss are from bog and upland heather and grass sites which are dominant over the “blanket bog” and “raised bog” Soilscapes and “Very acid loamy upland soils with a wet peaty surface”. In these soils the management is by grazing and burning. The Heather Burning Regulations, reinforced by GAEC requirement 10 (“Heather and grass burning”), preclude burning on deep peat soils but do not give methods for identifying the location of such soils, nor how deep is “deep”. Recent work suggests that there is a significant relationship between heather burning on deep peat soils and dissolved organic carbon in water. However, it is not just burning but the draining of such areas that is also contributing to losses of SOC and making them more vulnerable to loss. The data analyses have identified the types and location of soil with either high rates of loss in topsoil SOC under arable and rotational grassland and/or with SOC contents that are below a threshold set from the 1980 NSI. The first decision to be made before a monitoring scheme can be devised to populate a third set of “points on the NSI graph” must be the area over which the indicator is to measure change (England, Wales, Great Britain, UK) and the land use that the indicator is based on (arable, grassland, non-agricultural land). In addition, thought needs to be given to the policy answers that are required, for instance is the indicator a single national figure/trend, is the indicator measuring the success of a particular policy (Cross Compliance, Agri-environment schemes), the level at which policy drivers could be introduced to maintain or increase levels of SOC. In any re-sampling of the NSI in the near-future to determine trends in SOC the minimum sample size should be the sites visited between 1995 and 2004. In addition the field sampling team should record, as a minimum, details of the previous and present management together with details of the site topography. The former will help identify the processes behind changes in SOC and other soil parameters, and the latter will give more confidence in the ability of the sampling team to reach the target sampling point.

SQID: Soil quality indicators - developing biological indicators - SP0529

Time-Scale and Cost

From: 2004

To: 2004

Cost: £102,984

Contractor / Funded Organisations

Natural Environment Research Council

Thirteen potential bio-indicators have been identified that show the greatest promise for use in national-scale soil monitoring. These indicators should now undergo field evaluation to determine if they are sensitive enough to detect environmental change against a background of inherent spatial and temporal variability and if they provide consistent and reproducible results across the UK range of soil and land use combinations

The thirteen indicators identified are:

Indicator	**Method description**
Community Level Physiological Profile from soil respiration	Activity capability profile of soil community for soil carbon cycling
Potential enzyme activities	Enzyme activity for a range of soil biogeochemical cycles e.g. carbon, sulphur, phosphorus, nitrogen
Nematode community structure	Diversity and size of soil nematode community
Soil microbial community structure and biomass	Composition of specific groups in soil microbial community and soil microbial biomass
Ammonia oxidisers	Genetic profiling of soil microbial functional groups important for nitrogen cycling
Denitrifiers	Genetic profiling of soil microbial functional groups important for nitrogen cycling

Bacterial community

Genetic profiling of the soil bacterial community

Archaea

Genetic profiling of soil microbial functional groups important for carbon (methane) cycling

Methanogens

Genetic profiling of soil microbial functional groups important for carbon (methane) cycling

Methanotrophs

Genetic profiling of soil microbial functional groups important for carbon (methane) cycling

Actinomycetes

Genetic profiling of the soil actinomycete community

Fungal community

Genetic profiling of the soil fungal community

Microarthropod community structure

Diversity and size of soil invertebrate community

Scoping biological indicators of soil quality - phase II - SP0534

Time-Scale and Cost

From: 2006

To: 2008

Cost: £394,952

Contractor / Funded Organisations

Centre for Ecology and Hydrology

Description

The research will address specific requirements of the inter-departmental UK Soil Indicators Consortium to develop a set of policy relevant and scientifically robust indicators of soil quality.

SQID Phase II (Scoping biological indicators of soil quality) will field test a candidate suite of biological indicators for deployment in a national-scale soil monitoring scheme. The 13 indicators were prioritised through a robust assessment process in the preceding SQID project (SP0529) and show high relevance and applicability to large-scale monitoring of soils. The biological indicators under investigation have specific relevance to the maintenance of soil health, via the delivery of ecological processes, and are highly relevant to the soil functions of: food and fibre production, environmental interactions and ecological habitats and biodiversity.

The project will carry out two field trials over a two year period.
The first, in 2006/7, will assess whether the biological indicators are sensitive enough to detect environmental change against the background of inherent spatial and temporal variability (SENSITIVITY trial).

The second trial, in 2007/8, will assess whether the biological indicators provide consistent and reproducible results across the UK range of soil:land use combinations (DISCRIMINATION trial).

In the process, the project will establish a set of standard operation procedures that optimise interlaboratory comparability and overall reproducibility of results. These SOPs will be transferable to any soil monitoring scheme.

A range of statistical techniques will be applied to determine which biological indicators provide the most robust results, the metric required for monitoring and the degree of surrogacy between the different indicators.

The final product will be a report that provides a breakdown on the usefulness of each biological indicator to national-scale soil monitoring; the robustness of the different type of information obtained; the practicability, and therefore cost implications, of application of each indicator in a large-scale monitoring scheme and the relative value of the indicator with respect to others, including issues of complete or partial surrogacy relating to informing on ecological processes and the key soil functions.

This information can be used by UK-SIC to inform the specification of biological indicators for national-scale soil monitoring and for other policy-related soil issues. The information will also be invaluable to the wider scientific community since it will a comprehensive assessment of ecologically-relevant components of the soil community.

Organic Manure and Crop Organic Carbon Returns - Effects on Soil Quality (Soil-QC) - SP0530

Time-Scale and Cost

From: 2004

To: 2009

Cost: £988,476

Contractor / Funded Organisations

ADAS UK Ltd.

Description

The overall objective of the project is to provide an improved understanding of the processes and linkages through which organic carbon additions influence soil bio-physical and physico-chemical properties. Soil organic carbon (SOC) levels and turnover rates are intimately linked to the soil properties that are important in the maintenance of soil quality and fertility, and sustainable crop production. However, it has been difficult to distinguish the various processes and linkages through which SOC effects soil quality and fertility, associated crop productivity and environmental impacts. Moreover, many of the claimed benefits of organic carbon (OC) additions are largely based on anecdotal evidence. Building upon the previous research conducted in Defra projects SP0501 and SP0504, which evaluated the effects of `medium-term farm manure and fertiliser nitrogen (N) additions on soil quality and fertility" and the unique experimental resource provided by the network of seven sites, this project will seek to develop an improved understanding of the processes and linkages through which OC additions influence soil quality and fertility, and sustainable crop production. Additionally, at the four farm manure sites green waste compost and paper waste additions will be introduced as new treatments. An important aspect of the study will be to assess how soil properties will change over time, both in the short and long-term, which will be achieved through a combination of field measurements and modeling.

The maintenance and improvement of soil quality is a key objective for Defra policies on the sustainable use and protection of soils (e.g. First Soil Action Plan for England). Moreover, the importance of maintaining and indeed replenishing soil organic matter levels is a central component of many Defra & EU policies (e.g. EU Thematic Strategy for Soil Protection). This project will provide Defra with an improved understanding of the effects of OC additions, via repeated organic manure (farm manure, compost and paper waste) and fertiliser N additions, on soil quality and function. This will help to ensure that policy decisions are based on sound scientific data and do not compromise the long-term sustainability of UK soils.

Appendix 2

Soil analysis; notes form the IOTA Soil Workshop, 9 April 2008

Reference IOTA PACA Res Research Reviews **Laboratory mineral soil analysis and soil mineral management in organic farming** and the **Role, analysis and management of soil life and organic matter in soil health, crop nutrition and productivity.**

There are clearly shortcomings in our understanding of soils and in particular the analytical techniques and recommendations for organic farming. While analysis for pH, and K, Mg, organic matter and soil texture are reliable it is recognised that phosphate analysis is relatively unreliable as it does not indicate fully the phosphates that may be available from both mineral and organic matter sources.

However, soil analysis remains a very important technique, which should be used on a regular basis, provided it is in conjunction with an assessment of soil structure, including ensuring the structure is good, nutrient budgeting as a tool to help assess the suitability of a system for a specific farm, and crop observation and yield monitoring.

In the absence of any trials or monitoring to demonstrate soil nutrient levels for optimum crop production under organic conditions, there remains a question mark over the interpretation and appropriate management and mineral additions for soils under organic production. However, existing conventional, standard soil analysis techniques are useful. Used in the context of knowledge of soil type and the farming system being operated soil analysis is a valuable tool for the following reasons:

1. Long term monitoring to ensure that a farming system is working (e.g. sampling a field every year)
2. To identify major and minor nutrient deficiencies and pH, soil organic matter
3. It can help identify a particular problem of crop health or productivity
4. To avoid excess mineral or organic additions

Soil analysis should be an essential prerequisite to using inputs in organic farming and a requirement for organic certification , especially for the use of derogated inputs.

Tissue analysis is a valuable tool to use in addition to soil analysis to identify the cause problems.

There is no published research that backs up the comprehensive soil analysis methodologies and interpretation which are promoted under the following terms: nutrient balancing, cation exchange capacity, Albrecht and Balser soil analysis methodologies. There is no research evidence to support the concept of ensuring a correct nutrient balance or ratio of the cations. While the routine analysis of several minor elements can be valuable, it is of course expensive.

With regard to analysis of soil biology, the analytical techniques, be they microscope counting or DNA analysis, are a reliable indicator of soil micro-organism populations. There is no research evidence to enable us to know what management recommendations to make based on those results and with widely fluctuating populations according to soil conditions, for example, moisture, there remains a question mark over the usefulness of the technique.

Soil respiration tests – either laboratory or field tests – provide a good indication of CO_2 production and, hence, respiration and a crude indication of the biological activity of the soil.

While there is a question mark over the validity of some of the more comprehensive and soil biology analysis techniques and accompanying recommendations and a lack of information on interpretation of the data from others, these techniques may be helpful in an advisory context in order to help the farmer get a better understanding of soil nutrient levels and soil life and its management. There is of course a considerable financial cost involved in undertaking these more complex analyses.

The workshop identified a number of research priorities, including:

There is a need to identify organic crop response to soil fertility conditions as determined by Soil Analysis and to develop organic farming soil management (including appropriate fertiliser applications) to optimise crop production in the context of the whole rotation.
Soil ecology and biology management; knowledge of implications of soil ecology and how to manage it.

Ongoing field validation of soil analytical techniques including sending similar samples to a range of labs and comparing results and advice.

Incorporation of human waste (sewage) in organic farming

Management of soils under organic protected cropping

Other specific information which is needed

i. Nutrient contents of crops, manures etc in organic systems
ii. Assessment of Carbon sequestration & N_20 emissions from long term commercial organic farming systems

Mark Measures 5.5.08
Revised 12.5.09