Natural England Commissioned Report NECR100

Managing soil biota to deliver ecosystem services

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

This work was commissioned because many recent projects have highlighted the high potential of soil organisms to deliver important ecosystem services to agriculture and the wider environment, and also highlighted the strong, and frequently negative, impacts that agricultural land management has on soil biological diversity and function. A study was required which identified and highlighted positive practices and systems that farmers could adopt to harness the benefits of soil biological function more effectively. Such a study could be used as a tool to promote improved soil management practices to benefit both environment and food production.

The findings of this report have already been disseminated at several conferences, including the British Society of Soil Science, and the Soil Ecology Society/Royal Entomological society, as well as at a range of special workshops for policymakers and for farmers. The results have already proven to promote discussion and consideration of soil biological management among farmers and land managers. The research has highlighted a range of opportunities for developing soil biological approaches within farming, and these have been developed into a range of ideas and proposals for experiments, comparative (paired farm) studies, demonstration farms, advice tools and approaches. It is hoped that these will form the basis of either smaller-scale experimental projects, should funding become available, or of a major programme of activities under, for example, a collaborative EU-funded LIFE+ project. There is a current call from LIFE+ for projects to protect soil biodiversity and the functions it delivers.

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Further information
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Executive Summary

Soil organisms are hugely diverse and play a range of critical roles in delivering the ecosystem services that sustain terrestrial life. These services include many functions important to agriculture, such as retention and cycling of nutrients, directly promotion of crop growth or health, decomposition and recycling of organic matter, maintaining soil structure and improving water retention. Soil organisms also provide wider societal benefits such as maintaining both below- and above-ground biodiversity, increasing infiltration of water to prevent pollution of watercourses, disposing of organic waste, and breaking down pollutants and are also a source of huge genetic and chemical diversity with many potential medical, and other, applications. Recent reviews have highlighted the largely negative impacts of modern agriculture on soil biota and their function. This project aimed to evaluate practical opportunities for agricultural management to enhance the diversity, abundance and function of the soil biota, to benefit agriculture and the wider environment.

The project combined literature review with farmer workshops to evaluate a range of different farming practices that have potential to deliver benefits through the soil biota, looking at the likely mechanisms, benefits, and practical constraints and opportunities for farming systems. The project considered both systems-oriented approaches, involving management changes across the whole farm, and “point interventions”, which are usually short-term and target specific aspects of the soil biota or their environment

The literature review (Section 2 and Appendix 1 of the report) suggested that systems-oriented approaches, especially where adopted in combination, were more likely to deliver benefits to agriculture through the soil biota, as well as having wider environmental benefits such as reducing sediment loss, or enhancing of biodiversity. The systems-oriented approaches judged most likely to succeed were those which increased or diversified organic matter inputs; reduced tillage intensity and/or diversified cropping systems. Adoption of practices following these general principles are likely to increase the diversity, activity and biomass of soil biota by reducing direct negative effects of agricultural management. They are also likely to support the development of larger or more diverse communities of soil organisms by increasing the energy supply, substrate diversity, opportunities for plant symbiotic relationships, as well as by improving soil structure and resilience to create more, and more diverse, soil micro-habitats.

Opportunities to integrate practices for improving soil biological function are available for all farming systems, and are reviewed in Section 2 of this report. Potential practices include use of manures, bringing in compost or other organic inputs, returning crop residues, choosing crops for their residue characteristics or their plant-microbe interactions, no-till, green manures, cover crops, mixed cropping (e.g. for wholecrop silage), and more diverse grass swards. Probable benefits to agriculture include improved

crop productivity through better soil structure and water holding capacity, reduced fuel use, more crop access to nutrients through symbiotic associations, and reduced fertiliser requirements. Environmental benefits, besides enhanced biodiversity in the soil, include reduced diffuse pollution problems associated with poor soil structure, and lower greenhouse gas emissions.

At the project workshops, detailed in Section 3 of this report, farmers reported constraints to uptake of beneficial practices, including the lack of advice or guidance, and lack of field-trial evidence to support systems-level approaches. However, farmers had observed numerous benefits from employing some of these practices (reported in Appendix 3), and these benefits were further confirmed and explored through more detailed case studies (see Section 3.3 and Appendix 4). Farmers also had few tools available for measuring soil biological quality, and lacked contextual information to help them understand any results observed.

Methods for understanding soil biology are rapidly evolving and a suite of key biological indicators is being developed for national-scale soil monitoring. Inclusion of such indicators as standard measurements in soils research would help to deliver a more integrated understanding of the role of soil biota alongside soil chemical and physical condition in the assessment of soil function. Development of these indicators into tools that are accessible to famers, along with an understanding of their relationship to soil function, would also allow farmers to understand whether their management changes were having the desired impact.

Widespread adoption of farm practices following the general principles outlined in this report is needed to realise the benefits that good soil biological health brings to both agriculture and environment. To support and encourage adoption it will be necessary to progress research into specific practices tailored to farming systems and soil types. Demonstration farms, with monitoring, will help to communicate the benefits of working with the soil biota, and also quantify the costs and benefits. Behaviour change by land managers could be encouraged through available or new ELS/HLS groups of options to encourage systems-oriented approaches that promote the activity, biomass and diversity of the soil biota, and future advice on managing soil biology must be integrated with existing farm advice streams.

Technical Summary

Background

- The soil is home to a quarter of all living land organisms from a wide range of taxa. Soil biota is a collective term for all these organisms, which support many environmental processes vital to sustaining terrestrial life. The soil biota is central in delivery of a range of ecosystem services by soils, as a result of the breadth of enzymatic capacity within the species and the diversity of habitat niches in the soil environment.

- In comparison with semi-natural systems, farmed land is usually associated with simplified ecological systems and soil food webs. There are also significant differences in the biomass, activity and diversity of soil biota found in different agricultural systems.

- Many scientific reviews have concluded that the maintenance and enhancement of the diversity, activity, and biomass of soil biota is of benefit to all agricultural systems but recommendations for changes in practices to enhance soil biota are system-orientated and usually expressed in a very general way; individual management practices are rarely recommended.

- This project aimed to identify farm practices and systems that are likely to enhance the functioning of the soil biota both to support sustainable agriculture and to deliver ecosystem service benefits. The project also considered how integration of such practices into UK agriculture could be most effectively supported.

- Engagement with land managers is critical for effective uptake and practical implementation of any changed practices in agricultural systems. Therefore the project team brought together research scientists with famers and advisors currently engaged in developing management approaches to enhance soil biota and soil function.

- The project objectives were therefore:
    - To provide up-to-date critical review of the impacts of agricultural land management on the soil biota, and the role of soil biota in relation to soil functions, agricultural production and the delivery of ecosystem services and to identify land management techniques applicable to English farming systems which show the best potential for enhancing the function, and diversity, of the soil biota.
    - To work with UK farmers and advisors currently trialling and developing management directed at enhancement of soil biota to record and critically examine their experiences and to evaluate the costs and benefits of management techniques directed at enhancement of soil biota.

- To develop a small number of case studies which illustrate the use of key land management techniques which show the best potential for enhancing the function and diversity of the soil biota.
- To identify the potential of the techniques above to inform development of schemes and advice streams in England in the shorter term and to identify which techniques would benefit from additional research.

- The focus of the project was on the pre-dominant soils and land use systems under agricultural management in England and Wales; hence findings are not generally applicable beyond lowland agricultural systems.

Identifying key agricultural practices and systems to enhance soil biota through critical literature review

- There is relatively little information which allows us to describe how the interactions of climate, vegetation and soil factors control the activity, biomass and diversity of soil organisms, even without the additional disturbance of agricultural management.

- Studies of soil biota in agricultural systems employ a range of methodologies. The evidence of impacts of agricultural practices on soil biota is largely derived from either: i) observed impacts of long-term differences in systems between treatments or over time; or ii) short term monitoring of impacts of changes in a single practice. The approach used here was therefore to look for key principles and points of general agreement rather than to carry out a full and rigorous meta-analysis.

- Most of the literature has focussed on the negative impacts of agricultural practices on the soil biota. We have therefore needed to apply an understanding of likely responses of the soil biota and its function provided by the literature review to predict the impact of the range of farming practices and techniques identified as likely to support or enhance soil biota.

- Many of the agricultural practices that have been identified as likely to support or enhance the soil biota are systems-oriented approaches (which involve management changes across the whole farm system) that potentially have impacts on a range of soil properties and soil biota. For the review we have grouped systems-oriented approaches into those which:
  i) Manage the amount and quality of organic matter inputs;
  ii) Modify tillage practices (usually reducing intensity);
  iii) Diversify cropping systems.

  We also separately considered:
  iv) Point interventions which are usually short term and target specific aspects of the soil biota or their environment.

Amount and quality of organic matter (OM) inputs

- *Direct impacts on soil biota*
    - OM inputs provide a direct source of energy/ food for many of the soil biota. Therefore when applied regularly, OM inputs generally lead to an increase in the biomass of soil biota in all groups.
    - Variation in the decomposability of the OM inputs (often indicated by the C:N ratio) may increase species richness. There may be significant short-term effects of OM inputs within the soil food web (e.g. changes in predator/prey interactions) caused by the relative availability of energy/nutrients; some inputs have been shown to suppress pathogenic organisms.
- *Indirect impacts on soil biota*
    - Decomposition of OM inputs stimulates structure development and improves structural stability in soils. Soils with regular inputs of OM therefore have improved structural characteristics with positive benefits for aeration (in clay soils) and water holding capacity (in sandy soils) and giving a wider range of niche habitats.
    - Decomposition of OM inputs increases cycling of nutrients, hence stimulating plant growth, further stimulating C inputs to the soil biota through roots, root exudates and residues.
- *Wider implications*
    - Improvements in nutrient supply and soil structure both have direct benefits for crop growth. OM inputs therefore may reduce the indirect (fertiliser) and direct (cultivation) energy demands of agricultural systems and also reduce runoff and associated sediment loss.

Modified tillage practices

- *Direct impacts on soil biota*
    - All tillage operations have direct negative impacts on macrofauna so reduced numbers of tillage operations and/or increased duration of no-till periods are likely to lead to increased biomass of macrofauna.

- *Indirect impacts on soil biota*
    - Tillage immediately disrupts in connectivity of pores and water films. Reducing the occurrence or frequency of this disruption is likely to increase soil mesofauna biomass.
    - Changes in tillage lead to changes in the proportion of time where there is active root biomass in the soil, and cover of soil by plants or residues as well as changes in stratification of OM inputs within the soil. Reducing tillage has been associated with increased fungal biomass especially of arbuscular mycorrhizal (AM) fungi. These are plant mutualists that support plant growth through colonising roots and increasing their access to phosphorus and water. Reduced tillage also stimulates soil biota more generally as a result of increased OM inputs and increased stabilisation of niche habitats.
- *Wider implications*
    - Changes in tillage, especially use of non-inversion techniques, lead to changes in soil surface conditions, especially overwinter, which are likely to reduce runoff and associated sediment loss; changes in above ground habitat structure can also benefit above ground biodiversity. Reductions in fuel use through reduced tillage intensity will have a larger impact than changes in C sequestration in terms of the net C footprint of agricultural systems where tillage is minimised.

Diversification of cropping systems

- *Direct impacts on soil biota*
    - For soil biota that are strongly root associated, extended periods where key host plants are absent are already used to reduce populations of pathogens; unintentionally rotational management, especially crop selection, could also reduce the effects of positive plant/microbe interactions e.g. AM fungal effectiveness.
    - The use of monocultures or simplified rotations leads to simplification in the soil food web. Increases in plant diversity, whether in space or time, are very likely to lead to increase in species richness of soil biota through more diverse litter, exudates, rooting patterns, and plant associations. Management of the farmed landscape rather than fields *per se* is also important as field margins, hedges etc provide an important reservoir of

soil organisms that may recolonise disturbed areas, as well as themselves providing a diversity of niches for a wider range of organisms.

- *Indirect impacts on soil biota*
    - Changes in crops and/or the introduction of mixtures also lead to changes in crop cover and OM inputs together with changes in timing and type of tillage – these will have a range of direct and indirect impacts on soil biota and range of soil properties as outlined above.
- *Wider implications*
    - The use of monocultures or simplified rotations reduces both above and below ground biodiversity. Increases in plant diversity through the management of non-farmed land (margins, hedges, wetlands) or interventions to increase plant diversity within fields whether in space or time are most often targeted interventions to optimise wildlife habitat within the farmed landscape.
    - Increasing the diversity of crops, or of sown pasture species, is likely to increase the variety of pollen and nectar sources, and may extend the season over which these are available. This may help sustain pollinating insects, and support better pollination for other agricultural crops.
    - Monocultures of single variety crops have often been blamed for the increasing reliance on pesticides to prevent rapid spread and impact of crop pests. Developing a more diverse approach to cropping could reduce pesticide requirements, or prevent catastrophic loss of entire crops to disease or pests.

Point interventions delivering specific targeted management

- There is little evidence of long-term negative impacts of pesticides or fertilisers used singly or in combination at field rates, except where Cu-based products have been used as fungicides over a long period resulting in soil Cu accumulation to toxic levels.
- There are a range of indirect impacts of herbicides on soil biota via impacts on plant cover and changes in the amount/quality of crop residues. Any management practices which increase overall plant growth (crop and weed) may have benefits for soil biota through increases in root biomass, depth rooting and exudation patterns and crop residue returns.
- Cessation of soil fumigation associated with management of soil-borne disease in high value crops should lead to increases in the biomass, activity and diversity of the soil

biota. However, soils with a long term history of fumigation may continue to have distinct communities of soil biota with reduced species richness even after fumigation ceases.

- A number of species of soil biota have been identified and directly linked to biocontrol or plant growth promotion in soils. As well as enabling and developing indigenous populations of these organisms through systems level interventions, steps have been taken to isolate the organisms and develop inoculation mechanisms in an attempt to effect targeted biological enhancement of biocontrol or plant growth.

- Even where inocula are appropriate to the site and viable on application, it is difficult to ensure that any added organisms persist in the soil and form effective plant associations. Consequently measureable impacts of inocula are often seen only in greenhouse trials or similarly controlled conditions.

- Few targeted interventions are expected to have major implications for wider soil function, but adoption of such practices on-farm are likely to be linked with other management changes, including systems-oriented approaches, as described above, which will lead to a range of direct and indirect effects.

Integrated adoption of one or more practices

- Increased benefits seem to accrue where systems-oriented practices are adopted in combination. There is increasing evidence that increasing OM inputs (with increased diversity in OM types) and reduced tillage can act together to promote increased biomass, activity and diversity of soil biota.

- Within crop rotations, no till periods, ideally with increased OM inputs, seem to provide restorative phases for soil biota; overall increased resistance and resilience of soil biota and soil function seems to be associated with diverse rotations with no-till periods, such as ley-arable rotations.

- The systems-oriented recommendations summarised above (i.e. increase OM inputs, reduce tillage intensity, increase plant diversity) provide general principles that can underpin best practice advice. However, the specific practices and their combination which are most appropriate for a particular farm depend on interactions between soil type and farming system factors.

Supporting on-farm uptake of practices

- Measurements of soil biota and its activity are not included in soil analysis routinely used on farm; soil biological indicators are being evaluated for use in national-scale soil monitoring.

- Some simple observational methods are used in the field using simple keys (e.g. for earthworms) or on samples submitted to the laboratory (e.g. AM fungal colonisation). There are also simple field tests that have been linked to decomposition activity (e.g. cotton strip assay, bait lamina test).

- However, there is little guidance to support interpretation of measurement of soil biota (or biological indicators) to provide a guide to support changes in practice. Often the assumption is simply that "more is better". It is useful to measure trends through time for the same site/field or compare values between fields with different management. Nonetheless, to support farmer decision-making, measurements are of little use without a supporting framework of interpretation.

Farmers experiences of soil biota management – workshop results

- During February and March 2011, 9 farmer workshops were held around England; over 200 farmers and advisors attended the workshops in total. 50% of attendees also completed a pre-attendance questionnaire sharing "My soil story".

- Workshops aimed to attract farmers that actively practised good soil management and/or had an interest in soil biota, and capture their experiences and knowledge. Hence this did not provide a representative sample of farmers.

- Farming and growing systems of all main types within England were represented from a wide geographical spread. The majority of farmers (75%) attending the workshops were organic.

- The workshops used facilitated discussions to explore farmer perceptions of a range of land management practices which were considered likely to enhance or maintain soil biota and the broader on-farm implications of their use.

- Factors that increased farmer awareness of soils, soil biota, and selection of farm practices included:
    - Reassessment of farm management at the point of conversion to no-till or organic farming

    - Training and engagement associated with cross compliance and Catchment Sensitive farming, especially when focussed on soil structure.

    - Information from the internet, books, magazines, and conversations with other farmers.

- The most common practices in place were systems-oriented approaches: minimum/non-inversion tillage, overwinter stubbles/ later ploughing, locally adapted rotations with grass/clover leys, use of diverse seed mixes in leys, application of (local) waste organic matter and replacement of slurry by solid/composted manures.

- Point interventions directed at soil life, such as use of compost tea or microbial inoculants, were used by very small number of farmers. Where such interventions had been adopted they usually formed part of a set of changed practices, which included a range of system-oriented changes to the management of OM inputs and tillage. This means that their benefits to soil biota, agriculture and the wider environment cannot be easily assessed.

- Farmers had adopted these system-oriented approaches which benefit soil biota, for a range of reasons including fuel reduction, carbon sequestration and conservation of above ground biodiversity.

- Practices that had been adopted were selected on the basis of their ease/simplicity, in particular their fit to the farming system currently practiced and appropriateness for the farmers' soil types and enterprises. Where practices were more costly/difficult then positive demonstrable benefits were important.

- Constraints to the adoption of untried practices were mainly linked to lack of information or access to it, lack of farmer time and need for additional investment.

- The main issues relating to adoption of new practices that were raised by farmers at the workshops were:
    - A lack of robust independent information about the effectiveness, other implications, costs and benefits.
    - Assessment of practices should include a full cost-benefit analysis together with information on the impacts on product yield and quality, together with any information about implications for the soil biota.
    - A high degree of inertia about changing farm practice that needs to be overcome to effect change on farms; caution and risk aversion are more common than innovation.
    - Difficulty in accessing local sources of OM. Increasing haulage costs has particularly significant impact on bulky OM materials.
    - A need for more information and tools that could support them to make more effective decisions for their farming systems and evaluate the impact of practices in place.

    - Farmer-farmer learning was an essential mechanism but this needs to be supported through reports and practical demonstration not only of single practices, but also how to integrate effective enhancement of soil biota within everyday farming practice.

- Following the workshops, five case studies were developed showing examples of all the most common system-oriented approaches together with innovative use of other management practices to enhance soil biota based on the perceived effectiveness of the outcomes within the constraints of commercial practice. These represented a range of farming systems and include both organic and conventional producers. The integrated system of farm management was the focus of these conversations, rather than single practices, and as far as possible the case study was compiled in the farmer’s own voice.

- The workshops and case studies clearly demonstrated that innovative practice often deliberately targeted at enhancing the soil biota is already in place on commercial UK farms.

The potential of land management practices for enhancing the function and diversity of the soil biota

- Data on the benefits of many of the practices reviewed are currently incomplete. The ecosystem service benefits linked to most system-oriented approaches are not only expressed through their impacts on soil biota, but also provide wider benefits through greenhouse gas flux or water quality, which were beyond the scope of this project. Hence qualitative assessment of the costs of implementation was used in the assessment of likely uptake. It is however clear from the consultations with farmers that whenever practices are included in demonstration trials, evaluation of cost-benefit at the enterprise scale as well as effectiveness at field scale should be assessed.

- The three **general principles** that are most likely to deliver benefits through the soil biota are
    - increase OM inputs to soil
    - increase diversity of aboveground plant species
    - reduce tillage intensity

- While there is limited evidence available, it seems likely that increasing benefit for the soil biota (biomass, activity and diversity) accrues where systems-oriented approaches are adopted in combination.

- On-farm practices that increase the amount and manage the quality of OM inputs generally have positive benefits for soil biota, with expected enhancement of, or low risk to, other soil functions and the wider environment.

- In livestock systems, on-farm management changes to manure handling with reduced direct use of slurry and more on-farm composting provide an opportunity to enhance soil biota, mainly through reduced negative impacts of slurry application.

- In arable and horticultural systems, regular input of crop residues and repeated regular applications of waste OM (local and composted) have been shown to have significant benefits for soil biota. However, green waste composts are not universally available, and development of integrated waste management solutions will be needed to support long-term availability of OM inputs from off-farm to farmers.

- The broad-scale environmental impacts of OM inputs should be assessed carefully through life-cycle analysis, especially where materials might be processed specifically for land application (e.g. seaweed, biochar).

- More work is needed to assess whether there are specific benefits of composting OM input in reducing soil-borne disease as well as maintenance of soil OM contents and soil structure.

- Reduced tillage intensity with limited use of inversion tillage shows benefits for soil biota. However, these seem to be direct effects only for soil macrofauna; many of the impacts are mediated through increases in the amount or changes to the quality of OM inputs or changes in plant diversity.

- Where reduced tillage intensity is coupled with larger OM inputs it seems likely that additional benefits will accrue. Targeted use of OM inputs has been observed to increase soil structural and biological resilience thus allowing sustainable use of intensive tillage rotationally (for field vegetables, potatoes etc); however more research is needed to understand the role of OM and the soil biota in the resilience of soil functions.

- Reduced or no-tillage approaches are already widespread, but their environmental benefits have yet to be fully quantified. In particular more work is needed to assess changes in tillage approaches on soil biota and soil function e.g. the use of aeration within grassland systems and zero-till systems for cereals and oilseeds. Paired farm approaches may allow systems-level monitoring of impacts on soil biota and wider soil function (e.g. impacts on GHG emissions and agricultural pests).

- In arable and horticultural systems, diversification and /or the integration of green manures (including cover crops) into crop rotations have positive benefits for soil biota compared with monoculture or rotations with minimal break crops. Small but similar impacts are seen with diversification of swards or use of intercropping for whole-crop silage in grassland and mixed farming systems. However, there is currently little field evidence or demonstration to aid in on-farm selection of green manures or mixtures or to investigate the impacts on soil biota of particular cropping combinations.

- Increased attention to plant-microbe interactions in the rhizosphere during plant breeding and variety selection could lead to increased responsiveness to positive interactions with soil biota (e.g. affinity for AM fungal associations) as well as to improve nutrient/water use efficiency and resistance to soil borne pathogens.

- Green manures, cover crops and grass leys provide opportunities for increasing OM inputs to the soil in situ. More research is needed on both rotational planning and plant breeding approaches to increase OM inputs and enhance carbon sequestration whilst overcoming any potential constraints to the soil OM balance due to the availability and cost of OM imports.

- Laboratory studies usually only consider impacts of single agrochemicals, and more work is needed to assess the combined effects of typical pesticide and fertiliser regimes in the field. The few field-based studies looking at normal field application rates suggest that there is relatively little direct impact of fertiliser or pesticide on soil biota. Consequently precision farming approaches are expected to have relatively little impact.

- Repeated soil sterilisation can lead to very significant reductions in biomass and activity of the soil biota and changes to community structure. Hence, wherever possible the use of soil fumigants and/or sterilisation should cease. The changes to the soil biota may not be remedied by simply ceasing sterilisation where it has been used regularly. Remediation of these soils by addition of composts or inocula may be possible, but no research has been done to confirm this.

- Point interventions directed at soil life, such as the use of compost tea or a microbial inoculant, have largely been developed and studied in controlled conditions. It would be useful to study the added value of such interventions against a background of effective system level management where indigenous soil biota are maintained and functioning at high level, rather than in sterile growth media. Robust data on the distinct effectiveness of most point interventions under field conditions are not available.

- While farmers are able to make use of tools to measure soil chemical conditions they are not currently well equipped to make decisions that take soil biota into account. It would be timely to develop the current SQID review of methods to measure soil biota and their activity to provide an assessment tool for soil biota (and biological fertility) accessible to farmers. This should complement monitoring of soil quality more generally and integrate into existing farm advice streams.

- The general principles identified by this project fit with a range of other drivers for better soil management and will benefit soil life, increase sustainability of agricultural production systems and deliver wider ecosystem services. These general principles could be used as the headline messages in communicating effective soil management to enhance soil biota and good soil management in general. In the first instance, targeted information and training for advisors actively engaged in giving soil management guidance on farm will have the greatest impact; materials developed for this purpose should then be made more widely available.

- The research reported here demonstrates that there are clear opportunities for farmers to maintain and enhance soil biota to support agricultural production and provide environmental benefit. Many of these practices have already been integrated into conventional and organic farming systems and they are likely to become increasingly cost-effective as input costs continue to rise (diesel, pesticides, fertilisers).

- Development of robust and accessible soil biological tests will increase understanding and awareness of the soil biota among both farmers and researchers. Research into impacts of soil management should include measurements of soil ecology and function alongside soil chemistry, physical condition, assessment of yield, profitability and other environmental impacts and benefits. This will not only generate a better understanding of management impacts on soil biota, and how to mitigate these, but will also contribute to a better functional understanding of how soil biota can contribute to developing more sustainable and productive agriculture.

- Widespread adoption of farm practices guided by the general principles identified in this report will be needed to secure the benefits gained by ensuring good soil biological health for both agriculture and environment. To encourage adoption it will be necessary to progress research into specific practices identified above. Demonstration farms, with comparisons to standard practices, will help to communicate these benefits, but must be well-supported by scientific monitoring to demonstrate and quantify both costs and benefits. To encourage behaviour changes, available ELS/HLS options could be compared with the general principles identified here and, if necessary, new options developed to encourage systems-oriented approaches that encourage the activity, biomass and diversity of the soil biota. In all cases, this future activity must be integrated with existing farm advice streams.

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Section 1 – Project background

The soil is home to a quarter of all living land organisms, and the soil biota of England is of enormous importance as a major component of our country's biodiversity. Soil biota is a collective term for all the organisms living within the soil, excluding plant roots, and is sometimes also simply called soil life. The wide range of biological taxa occurring in soils (Table 1) and the relatively limited knowledge of their ecophysiology, in many cases, means that soil biota are often grouped by organism size (micro-organisms, microfauna, mesofauna and macrofauna) or according to trophic or other functional groups to describe and/or model community and ecosystem processes (Wall 2004).

The soil biota is an essential component of terrestrial ecosystems, and has been called the "biological engine of the earth" (Ritz *et al.* 2004). Because of the breadth of enzymatic capacity within the species and the diversity of niches in the soil environment (Table 1), the soil biota supports many environmental processes vital to sustaining terrestrial life and is central in the integrated delivery of a range of ecosystem services by soils (including soil functions such as nutrient supply for plant growth, water regulation, carbon storage, support for biodiversity and wildlife) as described in detail by Turbé *et al.* (2010). Within agricultural systems, the soil biota have a key role in crop pest control, regulating decomposition, nutrient cycling, formation and maintenance of soil structure and hence have impacts on crop yield and quality, soil carbon sequestration, water quality, flood control and remediation of pollution. Detailed consideration of links between the diversity, activity, and biomass of soil biota and soil function was presented in Stockdale *et al.* (2006).

Taken overall, the role of soil biota in supporting food production has been increasingly marginalised with the intensification of farming systems during the 20th century (Giller *et al.* 1997). Technological advances in agriculture, particularly in the second half of the 20th century, in tillage, agro-chemicals and plant breeding, have enabled food crops to be grown with decreasing regard for naturally occurring soil processes. Intensification of farming practices has also led to less variation among farming systems and their associated landscapes (Benton *et al.* 2003). In addition, most agricultural practices also affect a range of soil properties (both directly and indirectly) and hence also impact soil biota. Consequently farmed land is usually associated with simplified ecological systems and soil food webs compared to semi-natural systems (e.g. Culman *et al.* 2010). For example, compilation of the limited data on protozoan species richness in agro-ecosystems and neighbouring natural biotopes (Foissner 1997) showed that the species richness of testate amoebae was reduced by more than 50% under agricultural production so that only a residue of the original more diverse population was retained; there was much less impact on species richness of ciliate amoebae.

Table 1 Soil biota by 'species' groups and their key roles in soil summarised from Stockdale et al. (2006)

Prokaryotes: bacteria, archaea, actinomycetes	Free-living	• Decomposition and mineralisation of organic compounds (including agrochemical and xenobiotics) • Synthesis of organic compounds(humus, antibiotics, gums) • Immobilisation of nutrients • Mutualistic intestinal interaction • Resource for predatory microfauna • Formation of biofilms • Pathogens of plants • Parasites and pathogens of soil animals • Helpers in mycorrhizal associations • Some specialists identified by their particular role in soil processes e.g. methanotrophs, methylotrophs, butyrate oxidisers, nitrifiers, denitrifiers, and many more
	Symbionts	• Associative nitrogen(N)-fixers with legumes, N fixing shrubs and trees
Fungi	Free-living	• Decomposition and mineralisation of organic compounds (including agrochemical and xenobiotics) • Synthesis of organic compounds(humus, antibiotics, gums) • Immobilisation of nutrients • Mutualistic and commensual associations • Resource for predatory microfauna • Parasites of nematodes and some insects • Bind soil mineral particles and organic matter
	'Symbionts'	• Associations between arbuscular mycorrhizal (AM) or ectomycorrhizal fungi and many plant species − Mediate transport of water and ions from soil into plant root − Mediate plant-plant exchanges of carbon (C) and nutrients; − Regulate water and ion movement within plants − Regulate photosynthetic rate − Regulate C allocation below ground − Protect from root disease and root herbivores
Protozoa		• Predation of micro-organisms • Disperse micro-organisms • Resource for nematodes and predatory macrofauna • Vector of bacterial pathogens • Parasites of plants and other soil organisms

Table 1 -continued

Nematodes	• Predation of micro-organisms • Disperse micro-organisms • Root herbivores • Parasites of plants and other soil organisms • Predators of nematodes and other insect larvae • Resource for predatory macrofauna
Mites	• Predation of micro-organisms • Consumption and comminution of organic matter • Predators of nematodes and other insect larvae • Root herbivores • Host for a range of parasites • Disperse micro-organisms and nematodes • Resource for predatory macrofauna • Modify soil structure at microscales through production faecal pellets
Collembola	• Predation of micro-organisms and microfauna • Consumption and comminution of organic matter • Predators of nematodes and other insect larvae • Disperse micro-organisms and nematodes • Host for a range of parasites • Resource for predatory macrofauna • Modify soil structure at microscales through production faecal pellets
Enchytraeids	• Comminution of plant litter • Predation and dispersal of micro-organisms • Mix soil mineral particles and organic matter • Create pores/channels in soil and litter for movement
Earthworms	• Create pores/channels in soil and litter for movement • Directly consume organic matter • Mix soil mineral particles and organic matter • Support microbial growth within their gut • Disperse microorganisms and algae • Host for protozoan and other parasites
Soil dwelling arthropods	• Consumption and comminution of organic matter (OM) • Root herbivores • Predation of micro-organisms and micro-fauna • Dispersal of microorganism • Predators of other soil and surface dwelling organisms • Create pores/channels in soil and litter for movement

Significant differences in the biomass, activity and diversity of soil biota also have been shown in comparisons of agricultural systems. For example, significant differences in both abundance and community composition of soil biota have been shown in dominantly pastoral compared with arable agricultural systems (van der Putten *et al.* 2004; Jangid *et al.* 2008). Postma-Blaauw *et al.* (2010) found that conversion of grassland to arable land negatively affected both the abundance and functional diversity of soil biota with larger impacts on the abundance and diversity of taxonomic groups with larger body size (earthworms, enchytraeids, microarthropods, and nematodes) than smaller-sized taxonomic groups (protozoans, bacteria, and fungi). There are indications that changes in agricultural management practices "reducing the intensity of use of mechanical and manufactured inputs and (re)-discovering cost-effective ways to integrate biological inputs, will benefit below–ground biodiversity, particularly in lowland grassland and cropping systems" (Stockdale *et al.* 2006). For example, restoration of a less intensive management system (re-establishment of grassland on arable fields) was shown to increase species abundance (Postma-Blaauw *et al.* 2010), however, the original community composition was not restored within 4 years.

While it is often argued that maintenance and enhancement of the diversity, activity, and biomass of soil biota is of benefit within all agricultural systems (e.g. Doran and Smith 1987; Beauchamp and Hume 1997; Clapperton *et al.* 2003), conclusions of scientific reviews often indicate only in the most general way how this can be practically enacted at a farming system level. For example, Clapperton *et al.* (2003) in a review of the role of soil microbial biomass in controlling nutrient release and plant uptake conclude: "Ideally agroecosystems should be managed to maintain the structural integrity of the [soil] habitat, increase soil organic matter (OM) and optimise the C:N ratios in soil OM using cover crops and/or crop sequence." Commonly such recommendations are general and system orientated; individual management practices are not recommended. This seems to leave farmers without answers to a range of pertinent and practically important questions such as "how many cover crops and which ones, where the right balance (economic as well as ecological) is between minimising tillage and optimising weed control …" (Stockdale *et al.* 2006).

Engagement with land managers is critical for effective uptake and practical implementation. However, there has been little critical engagement between the research community and those farmers and advisors who are currently seeking to develop practical management approaches directed at enhancement of soil biota in the field. It is therefore timely to draw together understanding developed separately in the research and farming communities, explore how information about the importance of soil biota can be better communicated and to explore the potential for integration into UK farming systems of changed land management practices which enhance the function, and diversity, of the soil biota.

The project reported here aimed to identify farm practices and systems that are likely to enhance the functioning of the soil biota to both support sustainable agriculture and deliver ecosystem service benefits. The project also considered how integration of such practices into UK agriculture could be most effectively supported. The project objectives were therefore:

A1. To provide up-to-date critical review of the impacts of agricultural land management on the soil biota, and the role of soil biota in relation to soil functions, agricultural production and the delivery of ecosystem services.

A2. To identify a limited range of land management techniques applicable to English farming systems that show the best potential for enhancing the function, and diversity, of the soil biota.

B1. To work with UK farmers and advisors currently trialling and developing management directed at enhancement of soil biota to record and critically examine their experiences.

B2. To work with UK farmers and advisors to evaluate the costs and benefits of management techniques directed at enhancement of soil biota.

B3. To develop a small number of case studies which illustrate the use of key land management techniques which show the best potential for enhancing the function and diversity of the soil biota.

C1. To identify the potential of the techniques above to inform development of schemes and advice streams in England in the shorter term and to identify which techniques would benefit from additional research.

The focus was therefore on the pre-dominant soils and land use systems under agricultural management in England and Wales. Consequently the specific plant-soil interactions within important semi-natural systems, e.g. lowland heath – podzols; upland moors or lowland fens – peats, are not directly addressed and care should be taken in the application of the findings of the project beyond lowland agricultural systems.

To achieve the Objectives outlined above an integrated approach was taken drawing on the strengths of lead scientists at Newcastle University (Elizabeth Stockdale and Julia Cooper) and SAC (Christine Watson). This was linked with practical expertise in the farming sector especially amongst those individuals developing management approaches to enhance of soil biota and soil function. The project team therefore included a number of key farmers and advisors across England, who are currently trialling and developing management directed at enhancement of soil biota. The advisory group provided input and review at a number of stages including an early challenge to the findings of the literature review. Additionally they worked with the project leader to facilitate workshops with a larger number of farmers, growers and advisors across England to record and critically examine their experiences of the key land management approaches identified. Engagement with the industry in this way through the project sought to ensure that the findings are well grounded in the practical realities of UK farming systems and hence of direct relevance.

In the following sections, we will report on Objectives A (Section 2) and Objectives B (Section 3) before drawing together the findings from the research community and those farmers and advisors who are currently seeking to develop practical management approaches directed at enhancement of soil biota in the field to develop conclusions (Objective C Section 4).

Section 2 – Identifying key agricultural practices and systems to enhance soil biota through critical literature review

A range of farming practices and techniques have been identified as likely to support/enhance soil biota. Natural England provided an indicative list in their call for tender (Table 2) and there was a high degree of commonality between this list and the practices that the farmers and advisors who were part of the project team knew to be in use in UK farming systems (Table 2).

The indicative list of practices (Table 2) also provided a framework within which the critical literature review reported in Stockdale *et al.* (2006) was updated for this project. The focus was on recent developments (2006 – 2010) in the study of soil biota in farming systems with a particular focus on the impacts of practices that were seeking to support/enhance soil biota and which had potential for uptake within UK farming systems. The evidence base used here derives from a number of scientific studies employing a range of methodologies. Care always needs to be taken when comparing data collected in different ways, at different times of year and on different sites. Hence direct comparison of the results of different studies is difficult. The approach was therefore to look for key principles and points of general agreement rather than to carry out a full and rigorous meta-analysis.

There is relatively little information which allows the detailed interactions of climate, vegetation and soil factors that determine the activity or biomass of particular soil organisms to be described and quantified, even without the additional disturbance of agricultural management. The evidence of impacts of agricultural practices on soil biota is largely derived from either:

1) observed impacts of long-term differences in systems (where a number of practices have changed) e.g. comparisons of organic vs conventional farming systems; snapshots of woodland vs grassland vs arable systems or
2) short term monitoring of changes in a single practice e.g. additions of manure or comparisons of differences in tillage intensity without in crop residue management or variety choice.

Increasingly more complex systems with interactions of common management practices are being studied e.g. Overstreet *et al.* (2010); however the complexity of farming systems in practice (see Section 3) means that current understanding of impacts of agricultural practices on soil life is relatively incomplete. Much of the literature focuses on the likely impacts of agricultural practices (mostly negative) on the soil biota; therefore we have often needed to use expert judgement together with this literature review to predict the impact of the range of farming practices and techniques identified as likely to support/enhance soil biota.

Table 2 List of key practices considered to enhance soil biota for UK farming systems identified separately by Natural England and the project group. List order does not reflect any prioritisation in likely uptake or effectiveness

As indicated by Natural England in Appendix 3 of tender document	As identified by farmers and advisors group and known to be in practice to enhance soil biota (9th December 2010)
○ Addition of organic material (composts, paper waste, sludge etc.) in different states of decomposition.	• Use of green waste compost, paper waste, coffee grounds, treated sewage sludges – i.e. application of (local) waste organic matter • Use of biochar • Use of seaweed
	• Changes in on-farm manure handling – reduced use of slurry • On farm composting using a range of inoculants and advanced techniques to develop site specific composts • Vermicomposting
○ Use of compost teas and similar products as foliar or soil treatments	• Use of compost teas
○ Permaculture techniques	• Permaculture – no rotation (hence limited applicability)
○ No-till (including over-seeding in grasslands)	• No dig and deep mulching for intensive horticulture • Drilling directly into clover swards
○ Modified tillage practices	• Minimum intensity tillage • Non-inversion tillage • Overwintered stubbles / late ploughing
○ Controlling trafficking to reduce compaction impacts	• Controlled traffic
○ Longer-term grass leys	• Locally adapted rotations with grass/clover leys
○ More diverse seed mixes for grass leys (deeper rooting plants etc.)	• Introduction of deep rooting species and herbs into grassland
○ Leaving grass for longer periods following grazing, to allow more re-growth before reintroduction of grazing.	• Modification of grazing practices; use of some cutting and mulching within grazing systems

Table 2 -continued

As indicated by Natural England in Appendix 3 of tender document	As identified by farmers and advisors group as known to be in practice (9th December 2010)
○ Not employing soil sterilisation.	• *Not identified as a practice adopted directly to benefit soil biota*
	• Use of green manure crops e.g. mustard incorporated to provide soil fumigation effects though modification to soil foodweb –
○ Reduced use of agro-chemicals (including $CuSO_4$ used in organic systems)	• *Not identified as a practice adopted directly to benefit soil biota* • *Some advisors noted that use of $CuSO_4$ is being phased out in organic systems because of long-term toxic impacts*
○ Precision farming – more efficient/targeted use of chemical inputs to reduce impacts and inputs	• Targetting of inputs of fertiliser and pesticides through precision farming approaches
○ Use of mycorrrhizal inoculants	• Seed treatment with mycorrhizal inoculants, especially for tree/perennial crops • General use as broad scale seed inoculant for arable crops
○ Use of older crop varieties for enhanced mycorrhizal infection	• *Not identified directly – older varieties common in organic systems*
○ Use of inter-cropping, under-sowing etc. to enhance mycorrhizal nutrient transfer effects.	• *Not identified directly – intercropping common in organic systems*
○ Use of over-wintered catch crops to perpetuate mycorrhizal populations.	• *Not identified directly – catch crops usually included in rotations as part of N management strategies*
○ Application or management of Plant Growth Promoting Rhizobacteria (PGPR)	• Application of molasses based stimulants for microbial activity
○ Promotion of N-fixing mutualistic bacteria through crop choice/soil inoculation.	• Inoculation of legumes through seed treatments

A report to Defra (2010) grouped agricultural management practices impacting soil biota in terms of the scale of their impacts i.e. i) systems-oriented approaches that provide energy-containing substrates and/or seek to optimise soil habitat, as distinguished from ii) those that target specific often monotonic aspects of the soil biota or their environment (= point interventions). Such point interventions include biocontrol or inoculation with specific species (AM or ectomycorrhizal fungi, rhizobia) or mixed species cultures (PGPR, plant growth promoting fungi). In considering the expected impacts of practices from the short-list, we have further sub-divided systems-oriented approaches into those which seek to:

i) Manage the amount and quality of organic matter inputs;
ii) Modify tillage practices (usually reducing intensity);
iii) Diversify cropping systems.

We also separately considered:

iv) Point interventions which deliver specific interventions often targeted at individual species or functional groups within the soil biota.

The full literature review is presented in Appendix 1.

In the following sections, we will briefly describe each of the land management practices within the grouping and draw out a summary of the expected impacts on soil biota from the literature review, where possible noting impacts on the biomass, activity and diversity of soil biota, and soil function in relation to agriculture and other ecosystem services; an extended summary is given in Table 3 following the text.

2.1 Impacts on soil biota (biomass, activity and diversity) of practices which manage the amount and quality of organic matter inputs

Range of practices

Practices that increase OM inputs to soil include incorporation of crop residues and livestock manures produced on-farm. Straw and stubble burning was banned in the UK from 1993 and the incorporation of stubble and many crop residues is now common. Increasing crop yield also tends to increase residue returns (in roots and stubble even where straw is removed); Blair *et al.* (2006) clearly showed that soil OM increased with increasing crop yield as a result of residue returns with the benefit to soil increased where straw was also returned (e.g. soil OM increased more rapidly where straw was returned as predicted by the overall C budget of the systems). Hence measures which promote optimum crop yields in any system will tend to increase OM inputs through roots, stubble and residues. However, the price of baled straw has been increasing and 50-75% of cereal straw is still baled and removed for use in livestock bedding and power generation (Copeland and Turley 2008). In some cases the straw will be recycled on-farm into livestock manures, but in most cases, baled straw is sold and hence this potential OM input is lost to the farm.

The integration of cover crops into crop rotations in fields at risk of soil erosion has recently been promoted in the UK; the aim is to limit winter soil erosion and nutrient losses by using crops which are low cost, able to establish quickly and provide a green cover overwinter. A secondary benefit is the increased OM input to the soil when they are incorporated. Any changes to crop rotations that increase the duration of crop cover and/or include crops with a greater proportion of root material or incorporated residues are likely to increase OM inputs to soil.

Application of livestock manures on-farm provides a way of recycling nutrients and OM temporally and spatially within the farming system. On farm in the UK, animal manures from housed livestock are collected and handled both as solids (farmyard manure, FYM) and/or liquids (slurry); housing design largely determines the forms of manure produced on each farm. Application of livestock manures then may be as raw (fresh) materials or following storage and sometimes treatment. Active management of livestock manure as a valuable resource on farm is gradually replacing the treatment of manures as an inconvenient waste (Smith *et al.* 2001); this has been driven by the need for compliance with Nitrate Vulnerable Zones (NVZ) legislation, increasing fertiliser costs for which manures can provide replacement, and the need to reduce both smell nuisance and ammonia volatilisation losses. Currently the main approaches used on farm for manure treatment are i) composting systems or related technologies producing a useful solid product; ii) biological systems for liquid manures that lead to decomposition of the organic materials; and iii) separation systems concentrating solids which can then be composted while concentrating available nutrients in the liquid fraction (Martinez *et al.* 2009).

Increasingly farmers are looking beyond the farm gate for sources of OM inputs. Off farm sources of OM include a diverse range of materials, including livestock wastes from intensive livestock production off site, sewage sludge and by-products of industry e.g. food wastes, paper mill wastes. There is also increasing production of certified green waste composts (BSI PAS 100). A wide range of organic materials are now available commercially to farmers as soil amendments; see for example the list provided by Quilty and Cattle (2011). Most of these materials are produced from waste materials; however, careful life cycle analysis is needed to evaluate the broad-scale environmental impacts, especially where materials might be processed specifically for land application (e.g. seaweed, biochar). Biochar is a charcoal-like substance produced by the thermochemical decomposition of organic materials at elevated temperatures in the absence of oxygen (pyrolysis). Its application to soils has received attention as the C is in relatively stable forms and may have distinctive benefits for soil function and carbon sequestration. In general from a sustainability perspective, there is a positive benefit to recycling of 'waste' organic materials to land, particularly where wastes are produced, processed and disposed of locally.

Composting is the biologically-mediated oxidative processing of OM by a succession of microbial communities resulting in the formation of humified organic material; the process improves the stability and suitability of highly heterogeneous OM sources for agricultural and horticultural application (Hubbe *et al.* 2010). Composting can occur either in open-air windrows or in closed buildings or vessels, sometimes with gas collection and treatment; open windrowing is by far the most common. Successful composting is critically dependent on both the input materials (especially the ratio of C to N, the nature of the cellulosic component and particle size) and management of the composting process (e.g. moisture, aeration, temperature). Large numbers of local authorities now compost green waste (e.g. park and garden waste) and other biodegradable waste sources in response to the Landfill Directive. On–farm composting of external OM sources has provided a diversification opportunity for some farmers. In 2008-09, farmed land received

60% of the 2.85 million tonnes of the green waste compost produced in the UK (Association of Organics Recycling 2010). Composting on-farm may use on- and off-farm sources of OM as inputs. Where farmers are composting manures on-site, they may also prepare compost extracts or compost teas as plant foliar treatments or soil amendments, although this is rare in the UK. The preparation of compost tea usually involves steeping compost in water for a defined period under aerobic conditions, often adding other substances such as seaweed extracts, fish hydrolysates, or molasses to the mixture (Quilty and Cattle 2011). The resulting liquid is then applied as a foliar spray to reduce establishment of plant pathogens, or as a soil amendment to support soil biological fertility.

Vermicomposting is a method of treating organic waste materials using specialised earthworms (most commonly *Eisenia fetida*). As the worms digest and then excrete the OM, worm castings, or vermicasts, are produced. Leachates are drawn off as liquid fertiliser, and the whole remaining solid organic mass is used as a soil amendment either raw or more commonly after further composting. The process has been adapted to an industrial scale – in part to produce worms as fishing bait – and may also take place on-farm. The compost and liquid materials produced are mainly used at a small scale particularly in horticulture.

Direct impacts on soil biota

OM inputs provide a direct source of energy/ food for many of the soil biota, particularly to the primary consumers - bacteria, fungi and earthworms e.g. Bhogal *et al.* (2011) found a linear increase in the size of the soil microbial biomass with the amount of organic carbon added in livestock manures across a number of soils in the UK. The implications of these additions cascade through the food web (Figure 1). Consequently, when applied regularly, OM inputs generally lead to an increase in the biomass of soil biota in all groups. There is some evidence that where OM inputs are composted before addition greater increases in the biomass of the soil biota per unit C input are seen e.g. Fließbach *et al.* (2007).

Variation in the decomposability of the OM inputs (often indicated by the C:N ratio), particularly the inclusion of some inputs with high lignin contents, may increase species richness. The more varied the types of inputs the greater enzymatic capacity and hence great species richness amongst primary consumers that is required to effect decomposition. However, there is not clear evidence that the microbial biomass and associated food web becomes adapted and “specialises” in decomposition of the dominant litter type (St John *et al.* 2011). Evidence to date does not indicate that increased resource availability for soil biota will lead to reduced diversity (within the likely range of increases that are achievable in practice), possibly due to an interaction with the contemporaneous creation of greater niche differentiation within the soil. In above-ground ecosystems humpbacked relationships are often seen between species diversity and both resource availability and stress / disturbance (Hooper *et al.* 2005). It is clear that below-ground, consideration of inter-organism interactions and their relation to function can only take an understanding of ecological relations within the soil so far; it is essential to integrate spatial habitat factors (Stockdale *et al.* 2006).

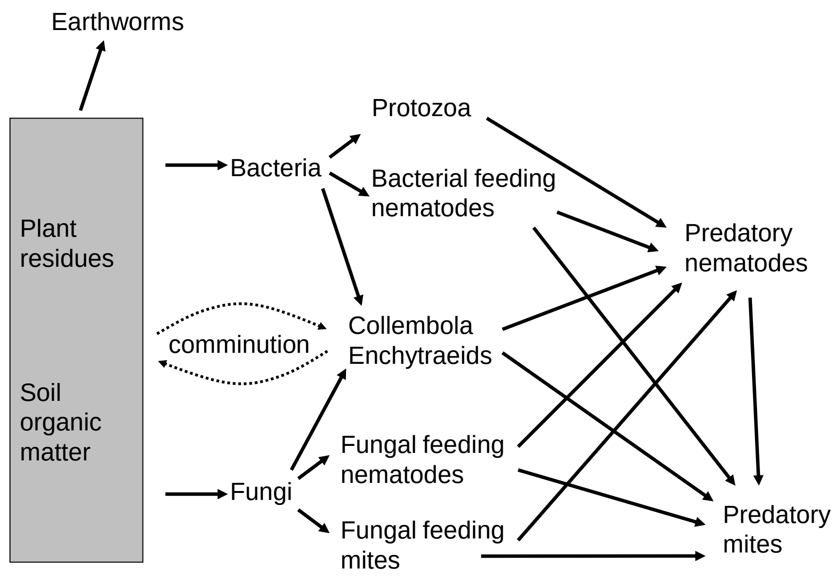

Figure 1 Schematic diagram showing the main interactions between the soil biota within the decomposition food web in soil (as originally presented in Stockdale *et al.* 2006)

Decomposability of OM inputs can also have significant short-term effects. Rapid decomposition of OM inputs can lead to high concentrations of both soluble C and NH_3/NH_4^+ in the soil solution (the same effect may result from slurry application) which has been shown to be suppressive of pathogenic microbes e.g. Bulluck *et al.* (2002). OM inputs have also been shown to be linked to reduced numbers of plant feeding nematodes in some studies e.g. Griffiths *et al.* (1994) probably as a result of modifications in nematode community structure due to changes in predator/prey interactions caused by the relative availability of energy/nutrients.

Indirect impacts on soil biota

The OM content of the soil is closely linked to the amount of OM input (Dick and Gregorich 2004). C cycling through decomposition of OM inputs stimulates structural formation processes after any disturbance and also improves structural stability in many soils. Increased OM inputs at the surface increase the activity of anecic earthworms, which create near-vertical burrows through the upper layers of soil and transport litter from the surface into the soil (Sims and Gerard, 1999). Consequently soils with regular inputs of OM also have improved structural characteristics with positive benefits for aeration (in clay soils) and water holding capacity (in sandy soils).

Communities of soil organisms are not specialised in decomposing the predominant plant litter type, in that organisms habituated to one type, will not be less capable to decomposing a different type (St John *et al.* 2011). However, different quality plant litter, resulting from different types of vegetation, results in different soil conditions, in terms of their acidity, moisture conditions, nutrient availability and other factors. Broad vegetation type, encompassing semi-natural and agricultural vegetation, has been shown to affect the diversity of broad groups of soil invertebrates (Simfukwe *et al*. 2010), and their response to environmental changes (Emmett et al 2010). Diversity within communities, and diversity of different assemblages of soil bacteria have been shown to be strongly associated with soil pH and vegetation characteristics across a broad range of British ecosystems, suggesting diversity is strongly influenced by the quality of plant inputs, and the influence these have on conditions (Griffiths *et al*. 2011).

Decomposition of OM inputs is often associated with increased cycling of nutrients occurring in organic forms (N, phosphorus, P, sulphur, S). OM inputs may also contain nutrients in plant available forms (N, P, potassium, K, and micronutrients) hence stimulating plant growth, further stimulating C inputs through roots, root exudates and residues.

Implications for soil function for agriculture and ecosystem services

The impacts of increased OM inputs for agriculture and ecosystem services have been widely discussed. Improvements in nutrient supply and soil structure both resulting directly from the decomposition of OM inputs effected by the soil biota have direct benefits for crop growth and also may reduce the indirect (fertiliser) and direct (cultivation) energy demands of agricultural systems. Improved soil structural stability has potential benefits for reducing sediment loss and for improving water regulation in agricultural catchments (Posthumus *et al.* 2011).

Increased OM inputs require careful management. Leaving crop residues *in situ* may increase the risk of disease and/or pest transmission between crops. Increasing N supply through mineralisation of OM inputs may lead to an increased mismatch of N supply and crop demand increasing risks of N leaching and denitrification. The impacts on greenhouse gas emissions from soils, C sequestration and consequent overall benefits for greenhouse gas balance are less clear and will depend on application conditions and the alternative potential use of the OM input (Powlson *et al.* 2011).

2.2 Impacts on soil biota (biomass, activity and diversity) of practices which modify tillage practices (usually reducing intensity);

Range of practices

Tillage is used to loosen soil, modify the structure of the surface soil to give an appropriate seedbed (known as the tilth), and control weeds and pests. Traditionally tillage systems on farm in the UK have used a mouldboard plough to invert a slice of soil and bury crop residue followed by other tillage operations with tines or discs to prepare a fine seedbed appropriate to the crop to be sown/transplanted. For potatoes and many horticultural crops cultivation is more intensive and may include steps such as de-stoning and bed forming. Reduced tillage systems have been developed, most commonly for the cultivation of cereal and oilseeds that use a sequence (often in a single pass) of tine and disc implements (Morris *et al.* 2010). These lift and shatter the soil removing any shallow compaction (tines) and cut and mix any crop residue of soil clods (discs) to give a fine tilth. Reducing tillage operations for seedbed preparation may lead to the need for increased herbicide use to control weeds. Cultivator drills are now common which combine these tillage steps with press wheels and a drill, so that the field moves from residue and stubble to sown tilth in a single pass. In reduced tillage systems a range of cultivation depths may be used, but depth of cultivation is usually shallower than in conventional tillage and there is no inversion. Both systems may also use sub-soiling cultivators to remove soil compaction at depth (30-40 cm) which may be the result of a plough pan or trafficking with other cultivation or harvest machinery when soils are wetter than the ideal range for trafficability.

No-till systems, often known as conservation tillage outside the UK, seek to cause the absolute minimal disturbance needed for successful crop establishment and ideally no soil disturbance at all. They are consequently akin, although at a very different scale, to the no-dig systems used in horticulture. Consequently a permanent or semi-permanent soil cover resulting from the residues of the previous crop is also maintained at the soil surface (Knowler and Bradshaw, 2007). No-till drills combine a thin disc and carefully aligned drill so that soil disturbance is minimal. In arable systems, no till is commonly associated with cereal/ oilseed cultivation. Bi-cropping approaches, most commonly the drilling of cereals into an established white clover ley have been developed in parallel (Jones, 1992), though there is little documented uptake by farmers in the UK.

In controlled traffic systems, wheels of all equipment (cultivation, management, harvesting) are restricted to compacted permanent traffic lanes, so that soil in the crop beds and traffic lanes can be managed respectively for both optimum cropping and trafficability (Tullberg *et al.* 2007). Controlled traffic systems have not been widely adopted in the UK – they are most common as a next step following adoption of reduced/no till systems.

Permaculture is much more than an approach to tillage and combines an ethical framework, a design approach and an understanding of natural ecosystems. Permaculture seeks to develop settlements that are sustainable, agriculturally productive, non-polluting and healthy. The resulting multispecies intercropping systems associated with permaculture are often known as forest gardens. As with no-till systems, they seek to effect minimal soil disturbance in planting and they also integrate perennial species. Allied approaches such as alley agroforestry have been shown to have potential applicability at larger scale (Quickenstein *et al.* 2009) but are currently little implemented in practice in the UK.

The main change in cultivation within grassland systems in the last decade has been the increasing uptake of non-ploughing approaches to deal with shallow compaction in soil as a result damage from livestock e.g. through the use of slitting aerators. Davies *et al.* (1989) showed that ploughing may not be needed under many circumstances to remediate compaction in grass leys and restore soil structure with consequent increases in grass production. A range of machinery is now available but relatively little comparison of different approaches to the regeneration of soil structure in grassland has been carried out. The floristic composition of pastures changes as a result of environmental and agricultural management and their interactions. It is possible to achieve sward regeneration through overseeding with grass/clover seeds rather than cultivation to improve forage quality and perenniality. However, it is not easy to achieve effective manipulation of the sward composition by overseeding approaches (Lemasson *et al.* 2008).

Direct impacts on soil biota

All tillage operations have direct negative impacts on the biomass of macrofauna with the largest impacts seen for earthworms and beetles (e.g. Postma- Blaauw *et al.* 2010), usually as a result of exposure at the soil surface and subsequent dessication or predation. Reduced numbers of tillage operations and/or increased duration of no-tillage periods within a rotation are likely to lead to significant increases in earthworm populations. There is limited evidence indicating a direct impact of tillage on overall fungal biomass, despite the disruption of fungal hyphae during tillage (Wardle 1995).

Indirect impacts on soil biota

Reduced tillage intensity is also usually associated with increase in the biomass of mesofauna (such as nematodes, enchytraeids and mites); tillage operations have immediate, though indirect, effects on these organisms through the disruption in the connectivity of pores and water films. These indirect effects will also impact on earthworms and other macrofauna and intensify the direct effects described above. Hence reduced numbers of tillage operations and/or increased duration of no-tillage periods within a rotation are likely to lead to increased biomass of both soil macro- and mesofauna (Van Eekeren *et al.* 2008). Earthworm numbers are further enhanced where additional food resources are available e.g. in cereal-clover bi-cropping systems (Schmidt *et al.* 2003).

As well as the extreme disruptive impacts of tillage which reduce the size of the soil structural units (peds) and change pore size distribution, reduced use of ploughing in grassland renovation, zero-till approaches in arable agriculture and no dig and permaculture approaches in horticulture also lead to increased periods of crop cover and/or soil mulching with residues. This can lead to the increased duration of active root biomass within the rotation, as well as increased soil cover – by weeds, as well as crops and residues. The increased duration of active root biomass has been linked to increasing colonisation effectiveness and increased biomass of AM fungi in no-till systems (Allison *et al.* 2005, Gosling *et al.* 2006).

In the short-term, tillage often stimulates the activity of bacterial decomposers as there may be a burst of aeration and the structural re-organisation can bring new (or previously inaccessible) OM sources into the reach of the soil bacterial population; bacterial predators (nematodes, protozoa) may therefore also be stimulated in the short-term. Repeated tillage without sufficient residue or returns or other OM inputs therefore tends to deplete soil OM content. Reduced tillage means less mechanical incorporation of crop residues which may lead to an increased stratification of the soil profile with increased soil OM content and associated biological activity in the immediate surface horizons.

Implications for soil function for agriculture and ecosystem services

Soil organisms have a number of key roles in the formation and stabilisation of soil structure (Figure 2) and hence improving the effectiveness of the biological processes of structure formation is likely to be linked to improved capacity of the soil to absorb high intensity rainfall events minimising run-off and regulate catchment-scale water flows. Supporting the biological processes of structure formation can also confer increased resistance to compaction arising during tillage and resilience to structural degradation (compaction); however, this is also closely linked to concomitant increases in soil OM content (Angers and Carter 1996) and the mechanisms supporting structural resilience are not yet well understood (Schlüter *et al.* 2011). Change in the overwinter habitat structure on farms together with the increased availability of seed and invertebrates to foraging birds has been suggested as a reason for the observed increase in numbers of farmland birds overwinter in winter cereals established by non-inversion rather than conventional tillage methods (Cunningham *et al.* 2005).

The activity of earthworms is important in maintaining the connectivity of transmission pores to depth which can improve infiltration rates, reduce runoff and sediment loss (Chan 2001). Hence structural management through cultivation should ideally be selected to support rather than disrupt biological processes of structure formation (driven by plant roots and soil biota). For example remediation of soil structural problems in grassland through aeration is likely to have benefits for earthworms rather than ploughing to reseed; however, a larger benefit would accrue where livestock management or use of heavy machinery e.g. during silage making did not lead to compaction.

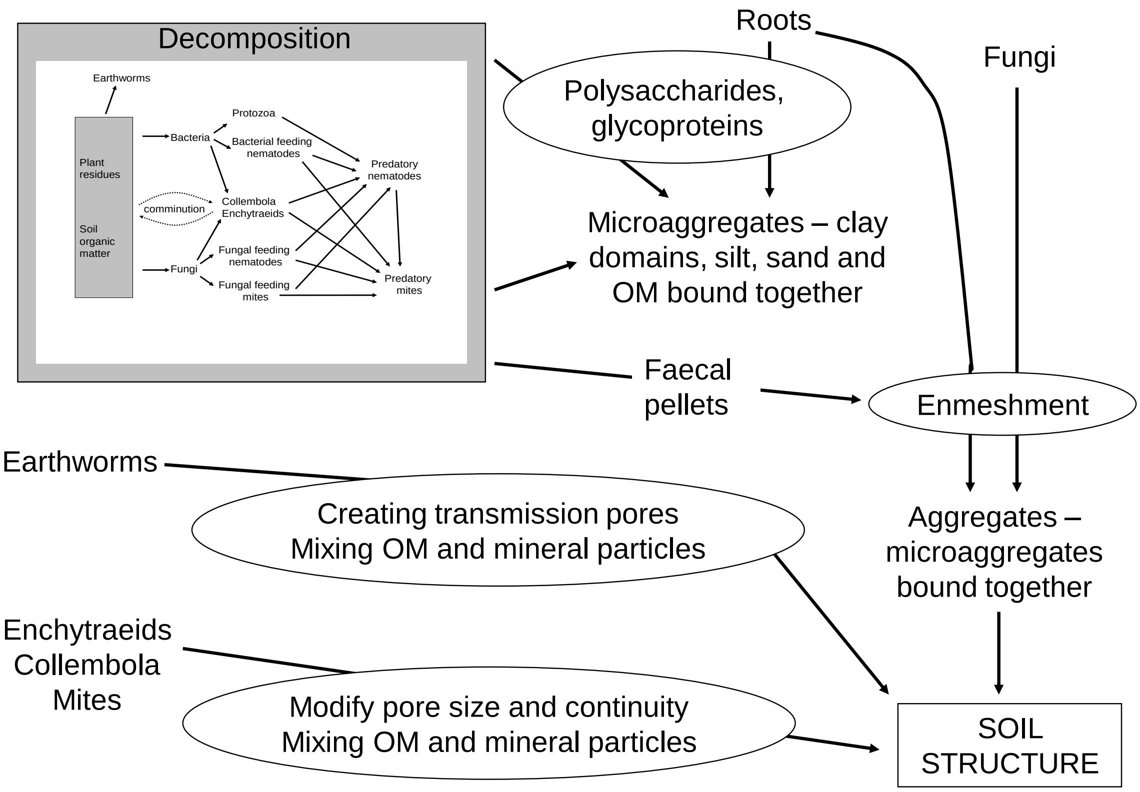

Figure 2 Schematic diagram showing the main roles of the soil biota in the development and stabilisation of soil structure, for detail of the interactions of organisms during decomposition see Figure 1 above (as originally presented in Stockdale *et al.* 2006)

The retardation of decomposition of soil OM by reducing tillage intensity does increase C sequestration (Powlson *et al.* 2011); however, the reduction in fuel use for cultivation associated with improved soil structure will have a much larger impact than sequestration on the net C footprint of agricultural systems where tillage intensity is minimised.

Improvement in infiltration and drainage through changes in soil structure can simply lead to a trade-off between routes of N loss (with an increase in leaching and reduced denitrification) and their associated environmental impacts. There are a number of constraints for farmers considering adoption of no-till or minimum tillage systems including reduced flexibility in cropping. While no till and minimum tillage systems are no widely adopted in the UK, their long-term impacts on pest and disease risks, weed burden, herbicide use and environmental benefits (e.g. N_2O emissions) have yet to be fully quantified.

2.3 Impacts on soil biota (biomass, activity and diversity) of practices which diversify cropping systems

Range of practices

Over decades and sometimes centuries, land managers have selected and arranged most of the plants that make up the farm landscape. The plants of copses and hedgerows, wetlands and river banks are sometimes deliberately chosen and planted; all have been managed and influenced both directly and indirectly through farm operations. The shape of farm woodlands and the number and locations of wetlands and hedgerows, buffer strips and uncultivated headlands are the result of human intervention.

Within fields, farmers choose which crop, which variety and when and where they grow it, hence determining species richness, genetic variability and organisation in space and in time of the crops grown. Crop management is also a key determinant of the associated weed populations. Agricultural intensification during the twentieth century has led to a simplification of the farmed landscape (fewer copses, wetlands etc), together with an increased occurrence of monoculture within fields (e.g. single species (often perennial ryegrass) leys) and reduced numbers and types of break crops in arable rotations (e.g. three year rotations of winter wheat, winter barley, oilseed rape). However, there are a wide range of practices common on farms which diversify vegetation communities and their structure e.g. more diverse seed mixes for leys, agroforestry, beetle banks, buffer strips, field margin management, game cover crops. There is also increasing interest in wholecrop silage; for mixed and dairy farms it is becoming economically viable to sow crop mixtures for silage particularly cereals and legumes (e.g. peas/barley, triticale/lupins). In cropping systems, undersowing is also increasing, as are catch crops and winter cover crops, providing a diversity of crops over time.

Direct impacts on soil biota

The presence or absence of particular plant species is critical to the survival of strongly root-associated species such as rhizobia, AM fungi and plant pathogens e.g. potato cyst nematode. Hence extended periods where host plants are absent can be used to reduce the populations of associated soil biota below critical levels so that no/ limited infection takes place if the host is re-introduced. This strategy is important in the cultivation of many crops e.g. brassicas and potatoes, where long rotations are used to manage the occurrence of soil-borne disease. The same mechanism also potentially reduces the effect of positive plant/microbe interactions e.g. Gosling *et al*. (2006) showed that the presence of fallow periods or monocultures of non-host crops also reduced the numbers of propagules (spores and hyphal fragments) of AM fungi and consequently the colonisation of subsequent host crops. There is also some evidence that increased attention to plant-microbe interactions in the rhizosphere during crop breeding and variety selection could lead to increased mycorrhizal responsiveness and improved nutrient/water use efficiency (Wissuwa *et al.* 2009). However, mycorrhizal responsiveness has not been targeted in modern crop breeding, and there is evidence that it may be accidentally selected against. For example Zhu *et al.* (2001) also found that mycorrhizal responsiveness of modern wheat cultivars, measured in terms of shoot P, was generally lower than that of older cultivars. Thus some modern crops may be less likely to benefit from mycorrhizal associations and propagate them to subsequent crops. Given the increased simplification of cropping systems, inoculation with critical beneficial microbes (rhizobia, AM fungi) may be required increasingly for common crops (e.g. peas, beans) due to a lack of effective indigenous propagules.

Each plant species (and often crop variety) contributes a unique root structure, amount and composition of root exduates and residues to the soil. These inputs of C drive the soil food web as discussed in section 2.1 above. Under laboratory and greenhouse conditions, the biomass and species richness of soil biota (bacteria, fungi, protozoa, nematodes, enchytraeids e.g. Griffiths *et al.* 1992) has been shown to be significantly different in the rhizosphere of different plant species (and sometimes even crop varieties). These observations are often not reproduced under field conditions and/or with plant species mixtures as a result of interactions of plant and soil factors (Marschner *et al.* 2001).

The use of monocultures, or simplified rotations, reduces both above and below ground biodiversity (Culman *et al.* 2010). The design of both the crop rotation and the farm landscape are critical in contributing to the conservation and enhancement of soil biota (Jackson *et al.* 2007). For many insect species, a range of habitat types is required during the species' lifecycle – loss of any habitat component could critically affect species survival even where the remainder of the habitat is in pristine condition. For soil biota (including crop pests), field margin habitats may provide an important buffer and maintain a source of organisms able to re-invade cropped land following disturbance (Blackshaw and Vernon 2006; Smith *et al.* 2008a).

Indirect impacts on soil biota

Diversified cropping systems are also associated with a range of sowing and harvest dates and an increased diversity of cultivation practices implemented at different times. Crop cover and OM inputs are usually increased and tillage type and intensity are diversified. These changes will impact a range of soil properties including soil structure which will have complex and interacting effects on the soil biota. Increased plant diversity and diversity of soil biota also means increased diversity in weed and disease pressures, above ground consumers and predators.

Implications for soil function for agriculture and ecosystem services

Increasing diversity in plant species is a direct target of some agri-environment scheme measures – particularly in relation to the conservation of species rich grasslands within the uplands and on the upland fringe. For example, work on restoration of upland hay meadows in the UK (Smith *et al.* 2008b) found that the conversion of bacterial-dominated soil microbial communities typical of intensively managed grassland systems to fungal-dominated communities, more typical of traditional systems was achieved by manipulation of plant species diversity through targeted seed /transplants followed by careful management of grazing/cutting and fertility inputs over 14 years. An increase in plant diversity, whether in space or time, is likely to lead to an increase in the species richness of soil biota; in forestry, tree mixtures have been shown to enhance OM decomposition and tree growth (Brown and Dighton 1989). However, to date, increasing species richness in the soil biota (or a component of it) has not been strongly linked to improvement in any soil function or their resilience (Mikola *et al.* 2002) in part due to high functional redundancy between and within species groups. In agricultural systems, which are typically in non-equilibrium states (plagio-climax communities), it is equally important to determine whether diversity affects how biologically mediated processes respond to further disturbance such as climate change (Stockdale *et al.* 2006); this is much less well studied.

Increasing the diversification of cropping systems requires careful management and may incur significant cost if new machinery is needed; seed costs are also often higher. The flexibility of weed management options (herbicides and cultivation approaches) may be restricted. Intercropping / crop and variety mixtures can cause problems with predictability and consistency of crop quality.

2.4 Impacts on soil biota (biomass, activity and diversity) of point interventions which deliver specific targeted management

Range of practices

Conventional farming systems use a range of manufactured inputs to support crop and livestock production. Mineral fertilisers are a major input into UK agricultural systems to meet plant nutrient demand; pesticides are a diverse group of chemicals used to control insects and other organisms that have adverse impacts on crop health. In intensive horticulture, fumigation of soils may be used to control soil borne pathogens (bacteria, fungi, nematodes) and weeds. These inputs underpin all conventional agricultural production; they are prohibited or very restricted within organic farming systems. Reduced use and/or more targeted use of these practices are considered as specific targeted management that may have positive impacts on the soil biota. The concept of “Precision Farming” involves the carefully targeted use of agro chemicals or other point interventions, in response to measured and mapped variations in soil and crop conditions within each field, and employs technological solutions that such as Global Positioning systems and variable-rate agricultural equipment.

A number of species of soil biota have been identified as having a positive impact on crop growth. As well as enabling and developing indigenous populations of these organisms through systems level interventions (which are implemented for a variety of reasons and are discussed above), a number of soil management practices or additives have been proposed to directly stimulate their activity e.g. molasses addition. There have also been steps taken to isolate and then apply these organisms as soil inoculants to promote their biocontrol or plant growth promoting functions (Berg 2009). As outlined above, the production and use of compost teas could also be considered as an approach to inoculation with a target population of soil micro-organisms.

Direct impacts on soil biota

Precision farming approaches will minimise the negative impacts of fertiliser or pesticide inputs or their associated formulations. However, there is little evidence of long-term negative impacts of pesticides used singly or in combination at field rates e.g. Gosling *et al.* (2006) showed few impacts of crop fungicides on root colonisation by AM fungi. Data on pesticide impacts has mostly been collected in laboratory microcosms which suggest that insecticides may have more direct toxic effects on non-target soil biota (e.g. protozoa, Foissner 1997) than other pesticides, but that the impacts of food resources and temperature often had larger effects. Hence reduced use of pesticides is expected to lead to few direct positive benefits for soil biota. Use of copper (Cu)-based products as fungicides has led in some orchards and vineyards to levels of Cu in soils (often > 100 mg/kg) that are toxic to replanting of the same crop or following crops and lead to impacts on the soil biota e.g. earthworms have been shown to have reduced growth rates and survival as well as reduced burrowing activity (avoidance) in Cu contaminated soils (Eijsackers *et al.* 2005); Cu is stabilised in soils and hence where it has accumulated there will continue to be long-term impacts, even where applications cease.

Soil fumigation has very significant short-term effects on the activity of the soil biota and, where sterilisation has been used routinely, there is a long-term cumulative effect on the biomass and species richness of the soil biota (Reeve *et al.* 2010). Hence while cessation of soil fumigation should lead to increases in the biomass, activity and diversity of the soil biota, soils with a long-term history of fumigation may continue to have distinct communities of soil biota with reduced species richness.

Rhizobial and mycorrhizal inocula are now produced for sale routinely. A number of PGPR and fungi (PGPF) have also been isolated from soil and the mechanisms of the positive interactions with plant species studied e.g. as PGPR *Pseudomonas*, *Bacillus* spp. and as PGPF *Trichoderma*, *Aspergillus* and *Penicillium* spp.. However, even where the inoculum is appropriate to the site and viable on application, it is difficult to ensure that the added microbes will persist in the soil and form effective plant associations (Deaker *et al.* 2004; Hoeksema *et al*. 2010). Other point interventions targeted at soil life such as use of compost tea or microbial inoculants for biocontrol or plant growth promotion are relatively un-studied. The conditions in compost, and in brews of compost tea, are likely to be very different from those found in soil, and this would suggest that the organisms that are cultured within compost tea may not remain highly active in the soil once applied. Positive effects are most often observed in controlled conditions (laboratory/ greenhouse experiments) and/or in soils with very low diversity or biomass of soil biota often as a result of repeated sterilisation to manage soil borne disease; more work is need to evaluate mixed microbial inoculants under field conditions (Dimkpa *et al.* 2009). The added value of such interventions against a background of effective system level management is not well understood. Stimulation of short-term activity of soil biota (e.g. through application of molasses) may have significant impacts for the farming system e.g. in stimulating decomposition of a particular crop residue but only have ephemeral impacts on biomass and diversity.

Currently the only point interventions which should be routinely recommended are inoculation of seed/ transplants with critical associative micro-organisms e.g. specific targeted rhizobia where a new legume is grown.

Indirect impacts on soil biota

Herbicides have a range of direct effects on plant cover (restricting weed emergence and/or growth and stimulating crop growth) which will influence soil biota indirectly. House *et al.* (1987) linked higher macroarthropod numbers in plots not receiving herbicides to impacts resulting from modification of soil cover and plant diversity. Glyphosate application (particularly late in the growing season) may lead to changes in crop residue quality reducing decomposability – however, Powell *et al.* (2009) found that such changes were not found consistently and strongly interacted with environmental conditions.

Where soil inoculants e.g. rhizobia, mycorrhizae, are successfully used to promote plant growth, then there may be additional positive impacts on the indigenous soil biota mediated through changes in root biomass, rooting patterns, amount and quality of root exudates.

Implications for soil function for agriculture and ecosystem services

Few of these targeted management practices are expected to have major direct implications for soil function in addition to the support of the function at which they are targeted e.g. rhizobia inoculation, if successful, will promote N fixation. However, adoption of such practices is likely to be linked with other management changes that might have direct effects on soil function and ecosystem services e.g. if fertiliser application were to be reduced due to inoculation, this should reduce the risk of diffuse pollution.

2.5 Integrated impacts resulting from adoption of one or more practices considered to enhance soil biota

There is increasing evidence that increased OM inputs (with increased diversity in OM types) and reduced tillage act together to promote increased biomass, activity and diversity of soil biota (Stockdale *et al.* 2006; Cookson *et al*. 2007; Overstreet *et al.* 2010). In the US, increased biomass and activity of soil biota has been shown following increased OM inputs in low-input sustainable agriculture systems compared with intensive conventional management approaches where residues are removed/burnt, tillage is intensive and no inputs of organic materials are made (Matson *et al.* 1997). Ley-arable farming systems, once common in arable areas of the UK, have also been shown to build restorative phases for below-ground organisms into the system (van Eekeren *et al.* 2008) and hence increase the resistance and/or resilience of the soil biota over the rotation as a whole – as shown for earthworm populations in Stockdale *et al.* (2006). Wardle *et al.* (1999) and Yeates *et al.* (1999) studied the impacts of fertiliser and pesticide inputs under field conditions and showed that in studies where soil OM levels are maintained or enhanced through return of crop residues (incorporated or mulched), there was no individual or cumulative impact of fertiliser and pesticide regimes. These studies confirm that soil OM has a key driving role in determining the biomass, activity and diversity of the soil biota and may also indicate the role of OM inputs / maintained soil OM levels in supporting the resilience of the soil biota communities. However, factors and management practices that increase resilience are also likely to vary for different below-ground organisms – e.g. for insect species, it is important to maintain a reservoir of individuals able to repopulate disturbed soils through management of the size, proximity and connectivity of the agricultural landscape and unaffected communities though appropriate management of field margins, buffer strips etc. In some circumstances, on-site management practices can also provide a reservoir population e.g. using tree saplings inoculated with appropriate mycorrhizal fungi.

It seems likely that increasing benefit for the soil biota (biomass, activity and diversity) accrues where systems-oriented approaches are adopted in combination. Hence systems oriented recommendations - e.g. increase OM inputs to soil, increase diversity of aboveground plant species, reduce tillage intensity - are likely to benefit soil life, increase sustainability of agricultural production systems and wider ecosystem services (Lal 2009). Increases in risks and negative impacts associated with adoption of the principles are relatively small and seem likely to be mitigated by care and tailoring of implementation of specific practices on-farm.

Recommendations to apply these systems-oriented approaches in combination do not provide farmers with specific practical on-farm guidance on which practices to use, rather they provide underpinning principles. Working from these general principles to determine the most appropriate practices for a particular farm depend on a range of other site factors; each combination of soil type and farming system may call for a different set of practices. Hence there is a need for increased site-specific farmer understanding of the impacts of their farming practices on soil biota to enable choice amongst the increasing menu of available practices (Quilty and Cattle 2011). Following consultations with farmers reported in Section 3, we will draw together their experiences with these general principles and seek to identify practical guidance for on-farm management and needs for further knowledge sharing and/or research.

Table 3 Expected impacts of key land management practices on soil biota and soil function in relation to agriculture and other ecosystem services derived from expert judgement following the literature review presented in Appendix 1. The full list of practices discussed by farmers is presented here; list order does not reflect any prioritisation in likely uptake or effectiveness

Land management practice	Direct impacts on soil biota	Other impacts on soil which are likely to affect soil biota	Likely impacts on soil function for agriculture and other ecosystem services
Managing amount and quality of organic matter inputs			
• Use of green waste compost, mushroom compost, paper waste, coffee grounds i.e. application of (local) waste organic matter. Repeated applications	• Provides energy / nutrient source for soil food web • Supports increased biomass • May increase species richness and evenness depending on OM quality – C/N ratio etc	• Stimulates structural formation processes after disturbance • Improves structural stability in many soils • Improves drainage in poorly drained soils • Improves water holding capacity in sandy soils • Fertiliser effects of nutrients supplied stimulate plant growth and C inputs via roots and residues	• Improves nutrient supply for plant growth • Improves soil structure and its stability – reducing sediment loss • Increases soil C content – C sequestration • Improves water balance, regulate water flows • Increases greenhouse gas production – increase soil respiration – CO_2 production; if soils become waterlogged increase N_2O production
• Application of biochar	• Little evidence of direct effects at field rates of application.	• Impact is dependent on highly variable bio char quality. • May increase protected habitat space for small organisms in pores, increase activity by co-location of resources and organisms, but also may have suppressive effect on biological processes.	• Increase soil C content in very stable forms – C sequestration • Other benefits claimed but limited evidence in temperate soils
• Application of seaweed	• Provides energy / nutrient source for soil food web	• Improves structural stability in many soils through release of algal polysaccharides	• Improves nutrient supply for plant growth • Improves soil structure and its stability – reducing sediment loss • Improves water balance, regulate water flows

Table 3 -continued

Land management practice	Direct impacts on soil biota	Other impacts on soil which are likely to affect soil biota	Likely impacts on soil function for agriculture and other ecosystem services
• Mixed methods for on-farm manure handling – reduced direct use of slurry and increased composting	• Provides energy / nutrient source for soil food web • Reduces direct toxic effects of soluble NH_4 • Reduces indirect toxic effects caused by osmotic shock	• Reduced fertiliser effects following nutrient stabilisation by composting; may reduce plant growth and C inputs via roots and residues compared with slurry use. • Stimulates structural formation processes after disturbance • Improves structural stability in many soils • Usually has small liming effect - increasing soil pH	• Improves soil structure and its stability – reducing sediment loss • Increases soil C content – C sequestration • Improves water balance, regulate water flows • Reduces NH_3 volatilisation losses • Reduces greenhouse gas production after soil application – reduced N_2O production. Less difference between manure management methods when CO_2 production during composting is accounted for.
• Using a range of advanced techniques to develop site specific composts on farm	• Targeted changes in species richness and evenness by manipulation of "quality" – C/N ratio etc • Targeted manipulation of biomass and species richness in composts as soil inoculant	• As for repeated application of OM above	• As for repeated application of OM above
• Vermicomposting	• Provides energy / nutrient source for soil food web • May increase species richness and evenness depending on "quality" – potentially manipulated through feedstocks	• Fertiliser effects stimulate plant growth and C inputs via roots and residues • As for repeated application of OM above	• As for repeated application of OM above
• Use of compost teas as soil treatments	• Targeted manipulation of biomass and species richness as soil inoculant • Limited evidence in field soils	• May have fertiliser effect stimulating plant growth and C inputs via roots and residues • Limited evidence in field soils	• Other benefits claimed but limited evidence in field soils

Table 3 -continued

Land management practice	Direct impacts on soil biota	Other impacts on soil which are likely to affect soil biota	Likely impacts on soil function for agriculture and other ecosystem services
Modified tillage practice			
• Minimum intensity tillage	• All tillage operations kill soil macrofauna – largest impacts on earthworms and beetles; reduced numbers of tillage operations lead to significant increases in earthworm populations	• All tillage operations that mix soil reduce connectivity of transmission pores to depth • Changes pore size distribution, disrupts pore connectivity • Mixes OM inputs throughout tilled soil	• Improve soil structure – reducing sediment loss • Improves water balance, regulate water flows • Reduces energy requirements of cropping
• No till includes non-inversion tillage compared with minimum tillage	• Allows development of anecic earthworm populations towards site carrying capacity.	• Increases connectivity of transmission pores from surface to depth • Increased profile stratification; higher OM contents in surface soils • Surface mulch of residues provides more suitable end of season habitat for surface dwelling arthropods	• Improves soil structure and its stability – reducing sediment loss • Improves water balance, regulate water flows • Increases soil C content – C sequestration • Diversifies farmed landscapes overwinter; provides feeding habitats for seed-eating birds • Reduces energy requirements of cropping
• Overwintered stubbles compared with winter cereals	• No direct effects expected	• Surface mulch of residues provides more suitable end of season habitat for surface dwelling arthropods	• Diversifies farmed landscapes overwinter; provides feeding habitats for seed-eating birds • Extends period of soil cover – reducing sediment loss
• Controlled traffic for all tillage and harvesting operations compared with random trafficking of fields	• No direct effects expected	• Reduces proportion of field surface area subject to potential compaction impacts - reduced area subject to anaerobic conditions, increased porosity in crop rows.	• Improve soil structure – reducing sediment loss • Improves water balance, regulate water flows

Table 3 -continued

Land management practice	Direct impacts on soil biota	Other impacts on soil which are likely to affect soil biota	Likely impacts on soil function for agriculture and other ecosystem services
• Use of livestock to reduce need for cultivation e.g. high stocking rates immediately preceding tillage	• No direct effects expected	• Mixing and compaction of soil by heavily stocked livestock grazing (especially pigs) reduce connectivity of transmission pores to depth • Fertiliser effects of nutrients supplied interact with potential compaction impacts on root growth	• Improves nutrient supply for plant growth as a result of livestock manures • Degrade soil structure – may increase sediment loss during and immediately following grazing • May increase risks of nutrient loss
• Drilling crops directly into clover swards compared with cultivation and establishment	• All tillage operations kill soil macrofauna – largest impacts on earthworms and beetles; reduced numbers of tillage operations lead to significant increases in earthworm populations	• Permanent ground cover of clover (usually white clover) provides food resources at soil surface (for earthworms) • Perennial root system providing inputs below ground through root exudation and turnover • Increases connectivity of transmission pores from surface to depth	• Nutrient supply for plant growth as a result of N fixation and residue turnover • Improves soil structure and its stability; permanent soil cover – reducing sediment loss and regulating water flow • Pollinator populations supported by clover nectar. • Increases soil C content – C sequestration
• Permaculture techniques • No dig and deep mulching for intensive horticulture	• No tillage – positive impacts for anecic earthworms and beetles • Surface resides and mulches provides energy / nutrient source for soil food web and supports increased biomass • May increase species richness and evenness depending on OM quality	• Permanent perennial root system providing energy and nutrient inputs below ground through root exudation and root turnover • Increased variety in rooting patterns • Increases connectivity of transmission pores from surface to depth • Increased profile stratification; higher OM contents in surface soils	• Increases soil C content – C sequestration • Improves soil structure and its stability; permanent soil cover – reducing sediment loss • Improves water balance, regulate water flows

Table 3 -continued

Land management practice	Direct impacts on soil biota	Other impacts on soil which are likely to affect soil biota	Likely impacts on soil function for agriculture and other ecosystem services
• Overseeing in grasslands compared with ploughed re-seed	• Reduced disturbance through tillage operations likely to better maintain earthworm populations	• Less disruption of perennial root systems; maintaining inputs below ground through exudation and root turnover • Maintains connectivity of transmission pores from surface to depth • Compaction issues may not be addressed leading to increased anaerobic conditions	• Maintains permanent soil cover – reducing risk of sediment loss • Maintains nutrient demand; likely to reduce nutrient leaching losses • Improves water balance, regulate water flows • Reduces energy requirements of sward regeneration
• Aeration of grasslands compared with ploughing to address compaction	• Reduced disturbance through tillage operations likely to better maintain earthworm populations	• Less disruption of perennial root systems; maintaining providing inputs below ground through exudation and root turnover • Fewer changes to pore size distribution and pore connectivity	• Improves soil structure and its stability; permanent soil cover – reducing sediment loss • Improves water balance, regulate water flows
Diversifying cropping systems			
• Locally adapted rotations with grass/clover leys compared with monoculture or minimal break crops	• Diversifies amount and quality of residue inputs modifying energy / nutrient sources for the soil food web	• More variety in timing and type of cultivation practices and duration of ground cover • Increased variety in rooting patterns • Increased diversity of hosts to support persistence of plant-associating organisms	• Diversifies farmed landscapes • Increases soil C content – C sequestration • Improve soil structure – reducing sediment loss

Table 3 -continued

Land management practice	**Direct impacts on soil biota**	**Other impacts on soil which are likely to affect soil biota**	**Likely impacts on soil function for agriculture and other ecosystem services**
• Integration of green manures into crop rotations	• Provides additional OM inputs as energy / nutrient source for soil food web • Supports increased biomass • May change species richness and evenness depending on quality – C/N ratio etc • Depending on crop species provides hosts for mutualistic soil organisms	• Increased variety in root biomass, rooting patterns, amount and quality of root exudates, amount and quality of residue inputs • Increased duration of ground cover	• Increased duration of soil cover – reducing sediment loss • Increases soil C content – C sequestration • Improves soil structure and its stability • Diversifies farmed landscapes
• Introduction of diverse seed mixes e.g. deep rooting species and herbs	• Diversifies amount and quality of root exudation modifying energy / nutrient sources for the soil food web • May change species richness and evenness depending on "quality" – C/N ratio etc • Depending on species mix provides hosts for mutualistic soil organisms	• Increased variety in root biomass, rooting patterns, amount and quality of root exudates	• Improves nutrient use efficiency, may reduce nutrient leaching risk • May improve soil structure and its stability
• Modification of grazing practices; use of some cutting and mulching within grazing systems	• No direct effects expected	• Changing patterns of defoliation are likely to lead to changes in root growth and exudation • Changing stocking rates likely to change risks of compaction of soil • Changing duration and timing of grazing likely to change amounts of livestock manures	• May improve nutrient use efficiency, and reduce nutrient leaching risk • May improve soil structure and its stability

Table 3 -continued

Land management practice	**Direct impacts on soil biota**	**Other impacts on soil which are likely to affect soil biota**	**Likely impacts on soil function for agriculture and other ecosystem services**
Specific targeted interventions			
• Not employing soil sterilisation	• Cessation should increase biomass, activity and diversity of soil biota. Fumigation shows immediate negative impacts on the activity of soil biota; repeated use leads to reduced biomass and species richness of all soil biota. • Long-term fumigation may lead to cumulative impacts on community structure, which may not naturally return on cessation.	• None expected	• Few impacts expected; cessation of sterilisation approaches are likely to be linked to other cropping or management changes which may have effects
• Reduced use of pesticides including $CuSO_4$	• Limited direct impacts expected; little evidence of negative effects at field rates of application • Some benefits may result from fewer applications of insecticides • Reduction or cessation of Cu inputs may not reduce impacts on earthworm populations if Cu toxicity has developed	• Reduced use of herbicides increases weediness, and hence increases variety in root biomass, rooting patterns, amount and quality of root exudates and duration of soil cover . • Reduced glyphosate application may increase decomposability of crop residues	• Few impacts expected; reduced use of pesticides may be linked to other management changes which may have effects • Reduces pesticide losses to water
• Targeting inputs of fertiliser and pesticides = precision farming	• No direct effects expected	• Few expected; minimises any negative impacts of inputs	• Few impacts expected; increase targeting of inputs may be linked to other management changes which may have effects • May improve nutrient use efficiency, and reduce nutrient leaching risk

Table 3 -continued

Land management practice	**Direct impacts on soil biota**	**Other impacts on soil which are likely to affect soil biota**	**Likely impacts on soil function for agriculture and other ecosystem services**
• Green manure crops e.g. mustard incorporated to provide soil fumigation effects Additional to "Use of green manures" above	• Root exudates and decomposition products with both positive and negative allelopathic effects on soil biota observed	• Root exudates and decomposition products with allelopathic effects on seed germination restricting root growth and hence impacting associative soil biota.	• May allow reduced use of pesticides and/or sterilisation
• Inoculation of legumes through seed treatments	• No evidence of direct effects on indigenous soil biota	• None expected • If successful in promoting legume growth may increase variety in root biomass, rooting patterns, amount and quality of root exudates.	• Range of impacts result from successful cultivation of leguminous crops supported by seed inoculation
• Use of mycorrhizal fungal inoculants to support tree/crop establishment	• No evidence of direct effects on indigenous soil biota • May provide added AM diversity through provision of mycorrhizal spores for association with subsequent crops	• None expected • If successful in promoting plant growth may increase variety in root biomass, rooting patterns, amount and quality of root exudates	• Range of impacts result from successful establishment of inoculated crop.
• Application of Plant Growth Promoting Rhizobacteria or Fungi	• No evidence of direct effects on indigenous soil biota • Carrier substrates may have impacts • May provide added bacterial/ fungal diversity but numbers added very small compared to indigenous population	• None expected • If successful in promoting plant growth may increase variety in root biomass, rooting patterns, amount and quality of root exudates	• Few impacts expected due to low efficacy of applied organisms.

Table 3 -continued

Land management practice	Direct impacts on soil biota	Other impacts on soil which are likely to affect soil biota	Likely impacts on soil function for agriculture and other ecosystem services
• Application of molasses based stimulants for microbial activity	• Short-term energy source for soil biota, particularly bacteria • If bacteria populations are stimulated then food sources for bacteriovores provided	• None expected • If applied to crop residues may increase decomposability • May cause short-term immobilization of plant available nutrient	• Few impacts expected
• Application of gypsum	• No evidence of direct effects	• Stimulates structural formation • May improve structural stability • Increases soil pH, changing chemical equilbria and affecting nutrient availability • Fertiliser effects of Ca and S supplied on plant growth	• Improve soil structure – reducing sediment loss

2.6 Supporting on-farm uptake of agricultural practices and systems to enhance soil biota

Measuring soil biota (biomass, activity, diversity) – tools at field/farm scale

Because of the important roles of the soil biota in delivering soil function, development of soil monitoring in England has included a review of biological indicators for national-scale soil monitoring (Defra SQID projects as reported in Ritz *et al.* 2009). This review considered the robustness of the different types of information obtained and the practicability, and therefore cost implications, of the use of each indicator in a large-scale monitoring scheme. It also considered the relative value of each indicator with respect to others, including issues of complete or partial surrogacy in relation to ecological processes and the key soil functions. Many of the indicators will undergo further testing for use for national scale monitoring and none are yet routinely used or interpreted on farms. The high cost and skill requirement to carry out these analyses will continue to limit uptake to support farm decision-making. However, once a minimum indicator set is identified for use in routine soil monitoring, these indicators may well be more widely adopted at farm-scale.

Laverstoke Park is the service laboratory most overtly selling soil biological analysis to farmers in the UK at present. Laverstoke Park can provide measurements of total and active bacteria and fungi, protozoa, nematodes and mycorrhizal colonisation of roots using a microscope (www.laverstokepark.co.uk/microbiology-services). The website does not provide a detailed of the methods but because they are based on microscopy, links to the SQID indicators are limited. However, some farmers are accessing this analysis despite its cost and using it to guide on farm management. There are also increasing numbers of accessible field keys available for soil macrofauna e.g. www.opalexplorenature.org/Earthwormguide. The issue of interpreting the data to guide farm management is discussed further in the next section.

Biological indicators (and measurements which provide surrogate biological indicators) are used for on-farm monitoring in some countries/regions. For example, the Ohio Soil Health scorecard asks farmers to observe the speed of crop residue decomposition. Formalisation of such observational methods for decomposition activity, include the cotton strip (or wheat straw) assay used to indicate microbial decomposition activity (Kratz 1998; Van Gestel *et al.* 2003). Measurement of respiration of fresh soil using the Solvita® test kit (www.solvita.co.uk/products/soil-life-test-kit.htm) is now recommended within the USDA soil quality test. This test was developed at Woods End Laboratory for use with composts and soils. It has been tested against more conventional methods for use in soils in the USA (Haney et al. 2008) but not in UK soils to our knowledge. Given the accessibility of hand-held CO_2 meters, this or similar in-situ tests might appeal to advisors. However, again the problem lies with interpretation to support management decisions. A more sophisticated and commercially available option is the Bait-Lamina test which estimates the feeding activity of soil animals, measured as the proportion of exposed bait consumed. This test can be used to indicate the activity of soil fauna (especially earthworms) rather than microflora. Jacometti *et al.* (2007) and Reinecke *et al.* (2008) have shown differences between agricultural management practices using these simple field-based tests. Römbke *et al.* (2006) have proposed the test as international standard. It may be suitable for use by farmers/advisors as it does not require any specialist measuring equipment. However the uptake within monitoring schemes of integrative methods which measure the function of the whole community have been limited by the availability of an appropriate control (Gardi *et al.* 2009). The USDA Soil Quality Test Kit (http://soils.usda.gov/sqi/assessment/test_kit.html) also includes observational counts of earthworm numbers amongst a further suite of chemical and physical indicators.

While there are a number of measurements of soil biota and its activity (biological soil indicators) currently in use in scientific research, there are no measurements routinely in use on-farm. Development of the existing approaches to provide robust and accessible tests for use on farm will increase understanding and awareness of the soil biota. Ditzler and Tugel (2002) tested hands-on indicators with a number of potential end user groups and concluded that regular use was likely to be limited to “farmers with fairly high level skills, specialists and agricultural consultants”. Current on-farm soil health/ soil quality systems used outside the UK have made some attempt to provide interpretation for farmers – but generally without differentiation by soil/cropping systems and many simply assume that ‘more is better’. The issue of interpreting the data to guide farm management is discussed further in the next section.

Provision of information to support changes in practice on-farm

In their carefully considered review of advisory support for land management, Garforth *et al* (2003) indicate that the appropriate form of knowledge transfer will vary; and except where the task is simply that of making information available, facilitation to provide assistance or support in using the information is also important. The most prevalent source of information used by farmers was other farmers (Garforth *et al.* 2003). Facilitated farmer groups (e.g. the Landcare approach in Australia; Department of Agriculture, Fisheries and Forestry, Australia, 2006) are also a commonly reported means of sharing knowledge and promoting learning among farmers. Producer groups, environmental focus farms and Monitor Farms are also being successfully used as a means of knowledge sharing in the UK. Deugd et al (1998) stress the most effective approach is to support innovation by increasing farmers’ control over the processes of research and emphasising the process of learning rather than the teaching of content. Such an approach works best where the main blockage is not access to information, but rather farmers’ adoption, understanding and integration of that knowledge into practice. Sherwood and Uphoff (2000) see the challenge for improving soil management as one of engaging farmers which then facilitates change. They suggest that any approaches used should engage farmers in processes of identifying and prioritising problems and opportunities, testing and evaluating innovations and being partners in sharing the information gained.

Increasing on-farm uptake of agricultural practices and systems to enhance soil biota will require not only measurements of soil biota, as described above, but also interpretation of the data collected to provide a guide to practice. While it is useful to measure trends through time for the same site/field or compare values between fields with different management, to support farmer decision-making with regard to changes in practice it is important to know at least the direction of the change required (Is more or less of the measured characteristic better?). Wienhold *et al.* (2009) describe on-going work in the USA on a soil management assessment framework (SMAF) which is aiming at producing scoring curves as a way of interpreting soil indicators. This is an interesting approach but it is not known how transferable such relationships would be to UK conditions. Merrington *et al.* (2006) established a tiered risk-based procedure for users to select indicators for soil sampling and monitoring in the UK and used an expert group approach to identify trigger values or workable ranges for a number of soil chemical measures and soil bulk density; they indicated that biological indicators were still only available as research tools.

Within broader soil quality frameworks for on-farm use, which include physical and chemical indicators, a simple scoring approach has been developed in the UK but the biological measures currently only include observations of earthworms and crop residues (Simply Sustainable Soils accessed via www.leafuk.org). Gonzalez-Quiñones *et al.* (2011) discuss the identification of target/ threshold values issue in some detail for soil microbial biomass data. This is being implemented within the soilquality.org.au framework, which links a set of physical, chemical and biological soil quality indicators with an interpretation and benchmarking tool, and is currently being rolled out from Western Australia nationwide to support better management of soils within the grains industry in Australia. In New Zealand, farmers are also able to benchmark the health/quality of their soils using the soil quality indicators (SINDI) web-based tool (sindi.landcareresearch.co.nz as described by Landcare Research, 2006). . Wander *et al.* (2002) report a participatory approach to developing such a soil quality benchmarking system as a result of farmer and researcher interaction in cropping systems in Illinois, which highlighted that farmers often have the desire to take soil quality into account in decision making but lack tools which actually enable this to happen in the field. There is currently little evidence linking farmer-based assessments (including visual soil assessment) to soil function/ performance scores.

The availability of robust biological indicators would enable famers to assess the impacts of management more robustly and research into the impacts of changes in soil management to include comparable measurements of soil biota (biomass, activity and diversity). It may therefore be timely to extend the work on biological indicators for national scale soil monitoring to include a consideration of appropriate indicators and their communication to support on-farm decision making in the UK. This will contribute to a better functional understanding of how soil biota can contribute to the development of a more sustainable and productive agriculture.

Section 3 – Farmers’ experiences of soil biota management – workshop results

The project aimed to draw upon the experiences of farmers and advisors that were already using or advising on management likely to deliver benefits through enhanced soil biological activity, diversity and biomass. The aim was to analyse information from farmers and advisors to identify constraints, opportunities, costs and benefits of the management applied. The project team included a number of key farmers and advisors from across England who provided input and review at a number of stages, including an early challenge to the findings of the literature review. Additionally they worked with the project leader to facilitate workshops with a larger number of farmers, growers and advisors across England to record and critically examine their experiences of the key land management approaches identified (Table 2).Through engagement with the industry in this way, the project sought to ensure that the findings are well grounded in the practical realities of UK farming systems and hence of direct relevance.

3.1 Farmer workshops – location and structure

During February and March 2011, 9 farmer workshops were held around England (Figure 3); venues were selected in response to farmer demand. It was not possible to organise a workshop in North Yorkshire/Humberside as had been planned, due to low levels of farmer interest. The land managers and advisors on the project team acted as facilitators for the workshops in each area. Two of the workshops formed part of existing scheduled events, and this resulted in one workshop being held just over the Welsh border. The aim was to gather information on the opportunities and constraints for improving management of the soil biota, and to identify practices for further exploration. The workshops did not aim to attract a representative sample of farmers but instead to attract farmers actively engaged in best practice soil management and /or with an interest in soil biota.

The workshops were open to all to attend, but attendance at some workshops was constrained by venue size. There were between 10 and 35 attendees at each venue with just over 200 farmers and advisors attending the workshops in total. Each workshop had a similar structure (Table 4) but timings were locally adapted to fit with the needs of farming systems and the training aspect of the workshop (handling and discussing soil as a habitat) was not always included. The talks presented a summary of the findings of the literature review. Facilitated discussions of farmer perceptions and on-farm implications of the range of land management practices took place within small groups (2-7 per workshop). The project leader led each workshop with the aid of a local facilitator.

Table 4 Outline workshop structure

Table Duration	Activity
15 minutes	Welcome by local facilitator
30 minutes	Talk 1 (What do we know about soil life?) and questions
60 minutes	Hands-on chance to use visual soil assessment keys on soil samples or in the field and discuss soil as a habitat for biota.
45 minutes	Lunch break
60 minutes	Discussion groups –5-7 participants engaged in facilitated conversations about practices currently used on farm to enhance soil biota and their constraints, together with opportunities for the future.
30 minutes	Talk 2 (How farmers can make the soil smile – what science tells us so far) and questions
15 minutes	Conclusions and next steps

Findings of the pre-attendance questionnaire ("My soil story")

About 50% of the attendees also completed a pre-attendance short questionnaire ("My soil story"; Appendix 2) on their farming systems, opinions and current practices used to enhance soil biota. Anonymised data of farm systems, soils and practices in use amongst this farmer group has been stored in a simple Excel-based database; this is available to download through the Natural England website from the same page as this report.

Farming systems

Farming and growing systems of all the main types within England and Wales were represented (Tables 5-9) and the geographical spread represented was wider than apparent from the workshop locations, with some farmers/growers having apparently travelled long distances to attend (Figure 3). Livestock systems were dominantly lowland systems; only one "hill farm" was indicated in the questionnaires returned. While the majority of the farmers (75%) returning surveys were organic, a sizeable minority of conventional farmers with a range of farming enterprises also completed questionnaires. Within organic farming systems, soil biota assume a more central role in plant nutrient supply and crop protection as both fertilisers and pesticides are restricted; hence it was expected that a large proportion of the participants would be organic farmers.

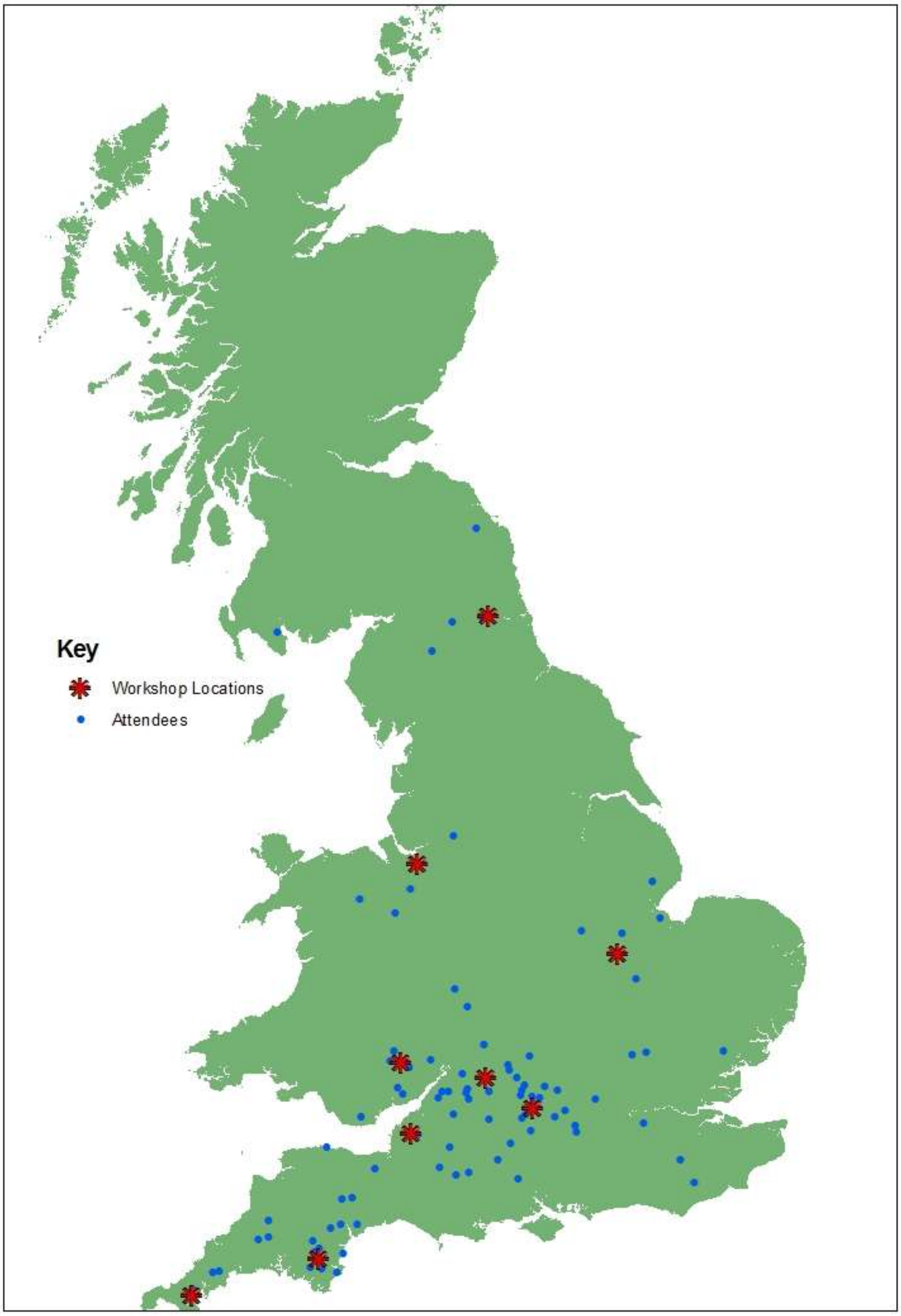

Figure 3 Origin of attendees and the locations of 9 farmer workshops held between 7th February and 3rd March 2011

Interest in soils and soil biota

A wide range of free-form answers was given when farmers were asked how they had become interested in soils and their management (Text box 1; all responses are given in the Excel database). While there is no single common thread, it is clear that conversion of the farm to either no-till or to organic farming had been a point at which the whole farm system was re-assessed from a new perspective and was recognised by some as the point at which their awareness of the soil biota had begun. The training and engagement with farmers in relation to management of soil structure (to reduce overland flow and diffuse losses of sediment) e.g. through initiatives related to Cross Compliance, Catchment Sensitive Farming had also provided a "way in" for many farmers. For many farmers access to information either published or via people was also essential in developing their interest and in supporting their selection of practices to integrate into the farming system.

Text box 1: Illustrative range of responses to the question: Why did you become interested in soils and their management?

"No response to some products when applied to crops. Crops suffering in extreme weather"

"Seeing how the same soil is different under different management"

"As an organic farm everything we produce comes from the soil; an understanding of the soil in each field is essential to produce high quality livestock / crops"

"Adopting min till and beginning to see the long-term effects"

" ... began to realise that there was a huge untapped reservoir of potential benefits lurking in the soil which conventional farming wasn't taking advantage of"

Practices in use on farm

Farmers were provided with a list of land management practices considered likely to enhance soil biota (as given in Table 3); on average (median), farmers were using 5 of these practices on farm with a range from 0 to 15 practices. When considered across all farming systems, the most common practices were all system-level interventions:

- Minimum/ non-inversion tillage
- Overwinter stubbles / late ploughing
- Locally adapted rotations with grass/clover leys
- Introduction of diverse seed mixes e.g. deep rooting species and herbs
- Application of (local) waste organic matter
- Reduced use of slurry and increased use of solid manures / composting

Point interventions directed at soil life, such as the use of compost tea or a microbial inoculant, were used by small number of farmers. Where such interventions had been adopted they usually formed part of a set of changed practices, which included a range of system-oriented changes to the management of OM inputs and tillage.

Based on their experience, the advisory group suggested that for most farmers the first and key step in uptake of land management practices likely to enhance soil biota is an explicit acknowledgement of soil biological fertility as a key part of the system. They noted that system-oriented practices which benefit biota may have been adopted for a range of other reasons including, but not only, fuel reduction, carbon sequestration and conservation of above-ground biodiversity. They also noted that farmers rarely simply adopt one practice which is thought to improve soil biota; these are adopted as part of an integrated policy of soil management. Consequently they advised that care be taken not to over-interpret the questionnaire results, described above, on adoption of practices.

A specific breakdown of the most common practices allocated according to the identified main farming enterprise is given in Tables 5-9 listed in order of farmer-recorded uptake (to the nearest 5%). The higher number of arable farmers responding to the survey means that their preferences (Table 7) strongly influence the most common practices noted overall.

Table 5 Most common grower-selected land management practices used in horticultural systems - 16 respondents. Growers each selected between 2 and 13 practices in total

Proportion of farmers	Land management practice
75%	Application of (local) waste organic matter
55%	Green manure crops
55%	Focus on on-farm composting
50%	Locally adapted rotations with grass/clover leys
50%	Use of no-dig and permaculture approaches
40%	Application of seaweed (inc. foliar feeds)
35%	Developing site specific composts e.g. using inoculation or other additives

Table 6 Most common farmer-selected land management practices used in arable systems – 31 respondents. Farmers each selected between 1 and 12 practices in total

Proportion of farmers	Land management practice
80%	Minimum/ non-inversion tillage
60%	Overwinter stubbles / late ploughing
40%	Targeting inputs of fertiliser and pesticides - precision farming.
40%	Application of (local) waste organic matter

Table 7 Most common farmer-selected land management practices used in mixed farming systems – 27 respondents. Farmers each selected between 1 and 11 practices in total

Proportion of farmers	Land management practice
65%	Locally adapted rotations with grass/clover leys
50 %	Minimum/ non-inversion tillage
50%	Reduced use of slurry and increased use of solid manures / composting

Table 8 Most common farmer-selected land management practices used in farming systems dominated by grazing livestock – 11 respondents. Farmers each selected between 2 and 11 practices in total

Proportion of farmers	Land management practice
60%	Introduction of diverse seed mixes e.g. deep rooting species and herbs
60%	Locally adapted rotations with grass/clover leys
55%	Overseeding in grasslands
50%	Focus on on-farm composting e.g. through more regular turning, monitoring of temperature

Table 9 Most common farmer-selected land management practices used in dairy systems – 12 respondents. Farmers each selected between 3 and 15 practices in total

Proportion of farmers	Land management practice
75%	Locally adapted rotations with grass/clover leys
60%	Reduced use of slurry and increased use of solid manures / composting
60%	Minimum/ non-inversion tillage
50%	Focus on on-farm composting e.g. through more regular turning, monitoring of temperature
50%	Introduction of diverse seed mixes e.g. deep rooting species and herbs
50%	Modified grazing practices

3.2 On-farm implications of land management to enhance soil biota – themes emerging from workshop discussions

All workshop participants actively engaged in the workshop discussions of the on-farm implications of the range of land management options for soil biota, sharing their experiences of the effectiveness and constraints to uptake. The reasons for adoption, expected impacts, constraints and limitations were different for each practice and often also on a farm or soil type basis. The full outputs on a practice by practice basis of these facilitated discussions are presented in Appendix 3. These findings are integrated with the information from the literature review on the effectiveness of practices in Section 4. General issues arising are summarised below.

Practices that had been adopted were most commonly selected on the basis of ease / simplicity, in particular their fit to the farming system as currently practiced and appropriateness for the farm's soil types. Where practices were more costly / difficult to implement, positive demonstrable benefits were important e.g. savings in fuel, increases in yield or quality, or observable improvements in soil quality. In some cases adoption of practices was driven by legislative requirements (e.g. NVZ requirements for slurry storage) or the requirements of assurance/certification (e.g. composting bought-in manures). At the farm-scale, one of the questionnaire respondents concluded that decision making is about: "*balancing what I'd like to do, what is cost-effective and what is proven practice*".

Constraints to adoption of untried practices were largely clustered around:

i) lack of information / advice or lack of access to it;

ii) lack of farmer time; and

iii) need for additional investment capital e.g. for new machinery, manure handling facilities.

Farmers felt that for most practices there was a lack of robust independent information about the effectiveness, other implications, cost and benefits of the land management practices considered. Many of the practices were used for a variety of reasons, not only because of a deliberate intention to enhance soil biota e.g. reduced tillage. They felt that farmers are not currently well equipped to make decisions that take soil biota into account – "*can we measure soil biota*?". They recognised that differences between seasons and/or farms in terms of weather patterns, weed burdens, soil type etc meant that "*what works somewhere else in that year might not work here this year*".

New practices that required increased time or attention on-farm, e.g. composting rather than simply stacking manures, were less likely to be taken up. In addition, it is not only the farmer who needs to be committed to adoption: "*everyone on the farm needs to be on board*". Farmers recognised that there is often a high degree of inertia about changing farm practice – caution and risk adversity are more common than innovation.

A particular concern for farmers in arable and horticultural systems with no/few livestock was access to OM inputs. Farmers found that often finding local sources of OM inputs is difficult and increasing haulage costs mean that the cost of all inputs is increasing. Bulky organic materials may therefore become too expensive to be considered and the use of off-farm OM materials though desirable may be taken beyond most farmers' reach.

In considering what could happen next, the farmers asked particularly for more information and tools that could help them to evaluate the impact of practices and make more effective decisions for their farming system (see Text box 2). At the end of the workshops, farmers discussed how their friends/neighbours could be interested in soil biota and encouraged to put into practice land management approaches that enhanced soil biota and its function. Participants noted that they represented a very small minority of farmers, in part because there is no commercial driver for most practices, and therefore no big marketing budget to apply to dissemination. One participant noted that "*most people have no interest; therefore the critical thing is to make people want to learn more and do more*".

Climate change and increasing resource scarcity were thought to provide opportunities for engaging farmer interest in more effective soil management, including but not only that of soil biota. They felt that sharing knowledge through farmer-farmer learning was an essential mechanism but that this should be supported through reports and practical demonstration not only of single practices but also how to integrate effective enhancement of soil biota within everyday farming. One participant suggested "*videos are now easy to share – what about soil biology TV on the web*". Many discussion gropus noted that there was a need for full cost-benefit analysis together with observations of impacts on product yield and quality, alongside the implications for the soil biota.

Text box 2: Illustrative range of responses when the question was asked: What should be done next to allow you to further enhance the soil biota through your management on-farm?

"It's all very interesting but a bit abstract; the principles you've talked about make sense but need to be fleshed out"

"Most of us need more basic information about soil to be able to work things out"

"I'm aware of the need to be site specific, not only for soil life, but not much advice is provided in a way that is clear how we can adapt it to fit our system"

"Support us to work it out for ourselves – help us measure our soil life and use that information in decision making"

"Give us tools to measure soil health and policies/ payments that make us use them"

"Give us easily accessible examples of what other people are doing; include both success and failure, we need both to learn and adapt things for our systems"

"We need to know about costs and the likely timescale for benefits – especially if structural changes are needed"

"We recognise that things that grow beneath the ground (potatoes, root veg. etc) carry the biggest threat; but as the farmer in your presentation says, if the market wants them how do we grow them most kindly for the worms – or more likely, how do we fix things once we've hurt them?"

3.3 Case studies – farmers working to enhance soil biota

An early draft of the literature review highlighted the high spatial and seasonal variability in the effectiveness of a number of practices. This limits the likely applicability of specific recommendations, and led to the recognition instead of general principles, based on analysis of the scientific knowledge, for improved management of soil biological functions. To balance this, and provide illustration and corroboration of the conclusions of the review, the project generated a series of case studies. These aimed to i) illustrate the application of the principles within commercial practice and ii) represent an example of the sorts of advisory materials that could support farmers in their development of more site-specific management decisions.

Following the workshops, a number of possible case study farms were identified which could provide a demonstration of the use of farm management practices that enhanced soil biota. It was recognised that for many farmers, these practices would have been adopted for other reasons, but that nonetheless case studies should be selected based on the perceived effectiveness of outcomes within the constraints of commercial farming practice. Around 14 sites were suggested or farmers volunteered themselves.

From these 5 case study sites were selected (Table 10). These

- represented a range of farming system types;
- included both organic and conventional farms;
- included examples of all the most common system-level interventions identified through the questionnaires;
- also showed innovative use of other management practices to enhance soil biota;
- were available for a visit in March and were easy to access by the project leader or advisory group member.

Table 10 Basic information for case studies selected

Case study number	Farm type	Practices in place that were discussed during on-farm interview, March 2011
1	Mixed	• Application of (local) waste organic matter • On farm composting using a range of advanced techniques to develop site specific composts • Use of compost teas as soil treatment • Integration of green manures into crop rotations • Introduction of diverse seed mixes e.g. deep rooting species and herbs
2	Horticulture	• Application of (local) waste organic matter • Integration of green manures into crop rotations • Green manure crops incorporated to provide soil fumigation effects – e.g. mustard
3	Arable	• Integration of green manures into crop rotations • No till / zero till • Overwinter stubbles / late ploughing
4	Arable	• No till / zero till • Overwinter stubbles / late ploughing
5	Dairy	• Reduced use of slurry and increased use of solid manures / composting • Use of compost teas as soil treatment • Use of mycorrhizal fungal inoculants

Interviews of the farmer/manager were carried out on-farm as part of a farm visit during March 2011. At one site (Case study 5) commercial soil biology analysis had been carried out across several of the farms and in a split field study undertaken by a farmer group thus enhancing the case study information. For all of the other case studies, possible sampling sites were identified but lack of time or the fact that the sampling window was not appropriate for the analysis required meant that no further additional analysis was undertaken.

The full case studies are presented in Appendix 4 and use additional text boxes link together the on-farm story with the scientific findings of the literature review. These case studies clearly show that innovative practice, often deliberately targeted at enhancing the soil biota, is already in place on commercial UK farms.

These case studies reinforce many of the points made by farmers in the “My soil story” questionnaires and at the workshops about the selection and adoption of practices together with the need to provide tools for farmers to be able to assess soil health robustly and to facilitate farmer/farmer learning.

Section 4 – Assessment of the potential of land management practices within UK agricultural systems to enhance soil biota and hence soil function

As reported above, the project drew on literature review and farmer experience to consider the potential of farm practices and systems to enhance the functioning of the soil biota to both support sustainable agriculture and deliver ecosystem service benefits. The scientific literature, and previous reviews of it (Defra 2010), confirmed that practices which:

- Increase the amount and manage the quality of OM inputs;
- Modify tillage practices (usually by reducing intensity);
- Diversify cropping systems;

benefit the soil biota (biomass, activity and diversity). While there is limited evidence available, it seems likely that increasing benefit for the soil biota (biomass, activity and diversity) accrues where such systems-oriented approaches are adopted in combination, such as required by organic farming standards or the practices of no-till (conservation agriculture) systems. These principles, particularly increased OM inputs and reduced tillage intensity, are common in the literature discussing options for increasing the sustainability of agricultural systems more generally. Farmers have adopted these system-oriented practices, which benefit soil biota, for a range of other reasons including, but not only, fuel reduction, carbon sequestration and conservation of above-ground biodiversity. Systems-oriented recommendations as outlined above are recommendations which are likely to fit with a range of other drivers for better soil management and will benefit soil life, increase sustainability of agricultural production systems and wider ecosystem services. Hence these could be used as the headline messages in communicating about effective soil management to enhance soil biota, and in fact, about good soil management in general. Farmers recognised these principles as good sense, but felt that there was a lack of specific guidance showing how these principles could be put into practice in particular farming systems.

Here we have brought together the findings of the literature review (Table 3) and the farmer workshops (Appendix 2) to consider impacts on soil biota and the wider environment, together with likely uptake (practicability and costs) to identify more specific practices that might be recommended to farmers (Table 11). Only qualitative comments on the costs of implementation are included in Table 11 e.g. farm labour, machinery requirements etc. Costs could be further refined e.g. through the use of farm management pocketbooks (such as Nix, SAC), and published Farm Business Survey data. However, there are insufficient data to make a full assessment of the benefits of many of the practices reviewed. The wider ecosystem service benefits linked to most system-oriented approaches are not only expressed through their impacts on soil biota, but also through their influence on other environmental concerns, such as greenhouse gas flux, above-ground biodiversity or water quality, which were beyond the scope of this project. It is however clear from the consultations with farmers that whenever practices are included in demonstration trials, both evaluation of cost-benefit at the enterprise scale and effectiveness at field scale should be assessed.

Table 11 Integrated consideration of key land management practices on soil biota and soil function linking expert judgement on impacts for the enhancement of soil biota with farmer feedback on likely uptake and effectiveness. Recommended practices have high practicability for widespread on-farm use with little further development, low net implementation cost and large benefits for soil biota. For each group of practices, land management measures are listed ordered in terms of recommended practices for widespread uptake by farmers/growers

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Managing amount and quality of organic matter inputs **Recommended practices**						
Use of green waste compost, mushroom compost, paper waste, coffee grounds i.e. application of (local) waste organic matter. Repeated applications	• Increase organic matter, biological activity • P and K supply • Improve soil structure • Enhance water retention • Reduce diesel use • Cheap form of nutrients, including micronutrients	**High** Can be limited by contamination with plastics, heavy metals etc Soil type may limit application windows	**Medium** Cost depends on access to local materials	**High** Provides energy and nutrient source for soil food web supporting increased biomass. Wide range of other benefits for soil function	**High** Waste disposal avoiding landfill Improvement in soil structure reducing runoff and diffuse pollution Increased storage of carbon Increases greenhouse gas production – increases soil CO_2 production; if soils become waterlogged also increase N_2O production	Limits to N application in NVZs Information about and access to local waste organic materials Perceived need for Practical demonstration of integration into farming systems with cost benefit analysis Assessment approaches that can be used by farmers to screen new /novel materials

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Mixed methods for on-farm manure handling – reduced direct use of slurry and increased composting	• Reduce pathogens and weed burden • Changes C:N ratio and stabilises material • Increases application flexibility • Reduce pollution risks • Meets NVZ requirements	**High** More handling required and hence may increase fuel and labour requirements	**Medium/ high** Depending on changes needed to livestock housing and manure handling systems, significant capital investment may be needed May need more straw / bedding and hence increases variable costs	**Medium** Change in quality of OM inputs; gives broader range of benefits for soil structural stabilisation, but may reduce N supply. Reduces direct toxic effects of soluble NH_4 and indirect toxic effects caused by osmotic shock	**Medium** Improves soil structure and its stability – reducing runoff and nutrient losses compared to slurry application. Reduces NH_3 volatilisation losses	Most common intensive livestock housing practices favour slurry collection Lack of information and demonstration of most effective integrated ways to handle manures at farm scale Most effective strategies need to be tailored to farm, soil type and take account of likely weather patterns.

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Managing amount and quality of organic matter inputs **Other possible measures**						
Vermicomposting As particular composting approach	• Rapidly breaks down organic wastes • Provides alternative source of income (worms) • Liquid feed is high in available nutrients	**Medium** Process needs some additional technical skill on site. May be best suited to small scale and/or high value production	**Medium / high** Needs additional space Labour requirement Relatively low cost capital set-up	**Medium / high** Provides energy / nutrient source for soil food web. No clear evidence of additional benefits beyond similar additions of other composted organic materials	**Low** Little additional environmental benefit over ordinary composting Liquid feed component may be more prone to leaching	Not widely demonstrated at farmer / commercial grower scale Cost/benefit analysis not reported
Using a range of advanced techniques to develop site specific composts on farm In addition to adoption of on-farm composting	• Tailor compost to crop need • Targeted applications in time and space • Can add minerals into compost heap and hence increase soil availability	**Medium / low** Currently most suited to small scale and/or high value production	**Medium / high** High capital costs associated with development of initial composting facilities; additional techniques add to labour requirements and may also increase variable costs	**Medium /low** May change species within the soil biota by manipulation of quality May be targeted inoculants of specific target soil biota	**Low** Little additional environmental benefit over ordinary composting.	Farmers and growers consider they lack technical know-how. Additional time required, but little cost-benefit data

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Use of compost teas as soil treatments In addition to on farm composting	• Used to inoculate soil with key organisms • Benefits to plant health, reduced pathogen damage.	**Low/medium** Complex procedures which need high technical skill on site. May be suited to small scale and/or high value production	**Medium / high** High capital cost of equipment for brewing and application Need for very high quality composts	**Low/ medium** Unproven benefits as part of an integrated approach to enhancement of soil biota.	**Low** No recognised environmental benefits.	Little/ no evidence of practical benefit in the field. Lack of knowledge and know-how in the UK. Perceived as “whacky”. May have value in remediation of previously sterilised soils
Application of seaweed As a specific OM input	• Extracts may be used as a short-term plant tonic • Source of iodine • Source of minerals /trace elements • Liming agent • Increase rooting extent and vigour	**Medium** Dependent on location Sustainability of sourcing is questioned	**High** Processed materials are high cost	**Low / medium** Provides energy / nutrient source for soil food web May improve structural stability	**Low** Widespread harvest of seaweed may be damaging to marine environment. Suitable as traditional management for machair grasslands.	Material difficult to source except in very localised areas

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Application of biochar As specific OM input	• Reported benefits for carbon storage • Reported benefits for nutrient holding capacity in sandy soil • Liming effect	**Medium / low** Methods for field scale application of fine powdery material not well developed.	**High** Materials are very high cost	**Low** No evidence of direct effects May have benefits for long-term C storage	**Low /medium** Low decomposition rate of added OM, hence may increase long term carbon storage Life cycle assessment information does not always favour biochar production No clear information on benefits at field/farm application rates in UK	Biochar materials are variable depending on source and production method. Material difficult to source in large quantities in the UK No clear information on benefits at field/farm scale

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Modified tillage practice **Recommended practices**						
Minimum intensity tillage Normally includes shallow disc and tine cultivators	• To reduce diesel consumption • Quicker than ploughing • Improve structure • Less soil disturbance • Reduce soil damage	**High/ medium** Soil specific requirements for machinery May increase problems with weed control Hard to implement for some crops (e.g. potatoes) Breaking leys may be difficult to achieve by min-till methods	**Medium / high** Capital costs of new machinery	**Medium / low** Reduced numbers of tillage operations lead to significant increases in macrofauna Increased stratification in the activity of the soil biota. Mixed evidence in the field as min-till includes a broad range of practices	**Medium** Reduced energy use in tillage Mixed evidence in the field as min-till includes a broad range of practices	Transition period can be associated with reduced yields and increased weed burdens May not be easy to find independent advice on machinery Perceived to be dependent on herbicide use Concern about soil compaction – needs careful soil-specific adaptation.

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
No till / zero till compared with minimum intensity tillage	• As min. till • Soil protection	**High** Cereals/ oilseeds **Low** Potatoes, field vegetables	**Medium** Very expensive drill Smaller/ fewer tractors	**High / medium** Limited field evidence in the UK Allows development of anecic earthworm populations towards site carrying capacity. *If combined with cover crops for weed control, then the benefits of green manuring indicated below also accrue*	**High/medium** Strong evidence for improvement in above –ground biodiversity Many studies show improved soil structure, and maintenance of soil macropores, which may generate less runoff. Reduced energy use in tillage. May increase C storage and reduce GHG emissions	Widespread farmer uncertainty about what zero till systems entail More dependent on herbicide use Limited detailed field-based evidence or demonstration in the UK.

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Modified tillage practice **Other possible measures**						
No dig and deep mulching for intensive horticulture	• Weed control • Improved crop yields • Better crop health • Maintains natural soil structure • Reduced energy use • Good for early cropping	**Low** Finding sufficient good quality mulch is difficult Not clear it can be expanded beyond small scale intensive vegetable production	**Medium** Hard to determine cost – benefit balance	**High** Surface resides and mulches provides energy / nutrient sources for soil food web and supports increased biomass	**High** As for no till with cover crops.	No easy way to up-scale practices
Drilling crops directly into clover swards compared with cultivation and establishment	• Weed control • N fixation supplies N to crop; N inputs reduced • Soil protection • Reduced cultivation costs	**Low/ medium** Not clear how competition between understorey and crop can be managed Not tried and tested	**Low** Not much evidence available to determine cost-benefit balance	**Medium / high** Limited field evidence Reduced disturbance through tillage operations likely to better maintain earthworm and macrofauna populations.	**High** Reduced runoff and diffuse pollution May reduce N fertiliser use as a result of N fixation Pollinator populations supported by clover nectar.	Some research studies; but limited farm-based evidence or demonstration

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Use of livestock to reduce need for cultivation e.g. high stocking rates immediately preceding tillage	• Save diesel • Effective interaction of crop and livestock	**Medium** May be particularly appropriate where pigs are on-farm Could also be used to support min till to break a ley	**Low** No data to enable cost-benefit analysis	**Low** Compaction might occur	**Low** Degrade soil structure – may increase sediment and nutrient loss during and immediately following grazing	Not studied in detail
Overseeding in grasslands compared with ploughed re-seed	• Cheaper than whole reseed • Improve/ maintain clover content • No lost production time while improving grassland • Enrich pasture diversity	**High** Suitable drill needed May need to have soil in good condition before these techniques can be successful	**Medium** May incur machinery cost Establishment can be poor; so low return for spend is a risk.	**Medium** Limited field evidence Reduced disturbance through tillage operations likely to better maintain earthworm and AM fungi populations. Energy / nutrient source for soil food web from longer duration roots	**Low** Maintains permanent soil cover – reducing risk of sediment loss	More clear guidance about when and how is needed. There is a lot of farmer experience about implementation that could be shared.

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Aeration of grasslands compared with ploughing to address compaction	• Rejuvenate existing pastures • Reduce compaction • Reduce runoff	**Medium** Some soil types have short-time windows for effective use of aeration techniques	**Medium** Machinery requirements Little/ no cost benefit analysis data	**Low** Reduced disturbance likely to maintain earthworm populations Maintaining soil cover and energy / nutrient source for soil food web.	**Low** Maintains soil structure and its stability; permanent soil cover – reducing sediment loss. Little evidence for long term benefit	Difficult to get independent advice about machinery Lots of farmer experience about implementation that could be shared • Could be coupled with overseeding with diverse species mix • Best followed by FYM/ compost application
Overwintered stubbles compared with winter cereal	• Soil protection in autumn • Green cover • Good for birds and other wildlife • Entry level stewardship points	**High** Fits easily within most arable cropping systems	**Medium** Substitution of winter cereal by spring crop may not be economically viable	**Low** No evidence of significant below ground benefits	**High** Strong evidence for improvement in above –ground biodiversity	May not be practical on heavier soils or where spring cultivation window very narrow
Controlled traffic for all tillage and harvesting operations compared with random trafficking	• Minimise yield loss due to compaction • Save fuel	**Low** Difficult to set up Implement widths don't always match	**High** Increased labour. Machinery and guidance system requirements	**Low** Little field evidence; improvements in soil structure may have benefits	**Low** Reduce in field runoff but preferential flow pathways created.	Site and weather pattern restrictions Little field experience or evidence to support uptake

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Diversifying cropping systems **Recommended measures**						
Locally adapted rotations with grass/clover leys compared with monoculture or minimal break crops	• Disease breaks enhanced • Fitting crops to soil types • Increase livestock growth rates with good clover levels in swards • Reduce fertiliser inputs • Reducing risk across farm	**Medium** More commonly adopted in organic farming systems Use of grass-clover leys may be limited to mixed systems Adds complexity to management	**Medium / high** Crop selection has implications for profitability	**High** Modifies amount and quality of energy/nutrient for soil food web through root and residue inputs Diversifies hosts for plant mutualists.	**Medium** Increased storage of carbon Diversifies farm landscape with strong benefits for above ground biodiversity	Information to inform local adaptation can be difficult to obtain as a result of increased homogenisation of agricultural practice New crop options often demonstrated as single crops –need more consideration of rotations in recommendations
Introduction of diverse seed mixes e.g. crop and variety mixtures, wholecrop silage, deep rooting species and herbs	• More balanced/ diverse diet for grazing livestock • Bring up minerals from deeper soil • Improve soil structure • Increase drought resistance of pasture	**High** Management of mixed swards whether for conservation or grazing needs more care	**Medium** Additional seed costs May be short-term costs for long-term benefit	**Medium / high** Modifies amount and quality of energy / nutrient sources for the soil food web through root and residue inputs Diversifies hosts for plant mutualists	**High** Greater plant diversity means greater invertebrate diversity Improves nutrient use efficiency, may reduce leaching risk	Lots of farmer experience about implementation that could be shared Little field evidence or demonstration to aid in on-farm mixture selection

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Integration of green manures into crop rotations	• Weed suppression • Overwinter cover • Retain nutrients • Increase soil OM • Improve structure	**High / medium** Timings not always right to fit to rotational need Crops highlighted were mustard, phacelia, oats, grazing/cereal rye, legumes	**Medium / low** Requires only minor change in cropping patterns (if any) Seed and management costs for green manures	**High / medium** Modifies amount and quality of energy/nutrient for soil food web through root and residue inputs Diversifies hosts for plant mutualists; but some species may have negative impacts e.g. non-hosts for AM fungi Benefits maximised where a diversity of green manures are used	**High** Diversifies farm landscape with benefits for above ground biodiversity Increased duration of soil cover – reducing sediment loss New source of C capture into soil – additional GHG benefit over existing C sources (manures, residues etc.)	Need to match crop species, rotations and soil type Potential persistence as weed needs to be understood Little management advice – not just which crops but best cutting/ grazing regimes etc

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Diversifying cropping systems **Other possible measures**						
Agroforestry, permaculture,	• Could increase resilience through diversity of cropping	**Low / medium** May be an option where woody biomass has market for biofuel Competition between crops needs to be understood within the system and carefully managed	**High** Major restructuring of farming system	**High/ medium** Modifies amount and quality of energy / nutrient sources for the soil food web through root and residue inputs Provides more hosts for mutualistic soil biota Limited field evidence	**High** Combination of trees and herbaceous vegetation diversifies farm landscape with benefits for above ground biodiversity Improves soil structure and its stability; permanent soil cover – reducing sediment loss	Some practical experience by growers at small scale in UK Some research studies; but limited farm-based evidence or demonstration. Long-term systems so may only suit owner occupiers
Modification of grazing practices; use of some cutting and mulching within grazing systems	• Weed (thistle) control • Livestock pathogen management	**Medium** Can be difficult to fit with farm needs Soil type / sward access can be an issue	**Low** Some increase in labour requirement to manage fencing	**Low** Limited field evidence	**Low** Little study of wider ecosystem implications	Range of possible modifications to grazing practice for sward and livestock benefit Some farmer experience, little best practice demonstration

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Specific targeted interventions **Recommended practices**						
Inoculation of legumes through seed treatments	• To improve establishment of legumes (lucerne, lupins, sainfoin) • Increased nodulation and N fixation	**High** Seed comes ready treated Big differences between fields in response	**Low** Part of seed cost	**Low** No evidence of direct effects on indigenous soil biota	**Medium** Range of impacts result from successful cultivation of leguminous crops supported by seed inoculation	Requirements understood for novel species, but not whether/when inoculation might be required for common crops (beans/clover etc) Farmers not aware of methods to check if inoculation is required
Ceasing use of soil sterilisation	• Not permitted under organic regulations and in some assurance schemes	**Medium /low** Only possible where alternatives for control of soil borne disease or persistent weeds in place	**Medium / high** May require change in crops Other management measures replacing sterilisation may be more costly	**High** If soil has been repeatedly sterilised over a number of years, then soils may need active restoration steps to benefit soil biota	**Low** Cessation of sterilisation approaches are likely to be linked to other cropping or management changes which may have effects	Sterilisation is a key management practice in many high value cropping systems Relatively limited land area affected

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium/ low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Use of mycorrhizal fungal inoculants to support tree/crop establishment Where obligate	• To support establishment and growth of trees/ crops	**Medium** Seed/ transplant comes ready treated	**Low/ medium** Part of establishment cost	**Low** Improved mycorrhizal infection of treated crop May provide spore reservoir for subsequent crops No evidence of direct effects on indigenous soil biota	**Low** Range of impacts result from successful establishment / growth of inoculated crop	Requirements for specialised crops reasonably well understood
Specific targeted interventions **Other possible measures**						
More general use of AM fungal inoculants	• To stimulate mycorrhizal infection in field crops especially after intensive cropping • To improve uptake of P	**High** General AMF inoculum accessible and used as seed treatment	**Medium** Increased "seed cost" May also need machinery adaptation	**Low** As above Little field evidence	**Low** Little study of wider ecosystem implications	Little evidence of efficacy Some on-farm use and demonstration, but little evidence of impacts to guide more widespread adoption

Table 11 -continued

Land management measure	**Rationale for adoption on farm**	**Practicability (high/ medium / low)**	**Implementation cost (high/ medium /low)**	**Expected benefit for soil biota (high/ medium/ low)**	**Expected benefit to wider environment (high/ medium/ low)**	**Issues and constraints affecting widespread adoption in the UK**
Reduced use of pesticides including $CuSO_4$	• Improve biodiversity especially on field margins • Reduce costs	**Medium** Alternatives measures needed	**Medium** May require significant changes in crops/ rotation	**Medium / low** Little evidence of negative effects at field rates, so direct impact of reductions not expected May have benefits if weeds increase diversity of in-field plants	**Medium** Reduces pesticide losses to water. Reduced use of pesticides may be linked to other management changes which may have effects	Consequences for yield not always well understood Potential for development of resistance
Targeting inputs of fertiliser and pesticides = precision farming	• Reduce variable costs of inputs • Reduce application rates by increasing specificity • Fit with Catchment Sensitive Farming	**Medium** Training and willingness of operators essential Needs good knowledge of underlying soil and interactions with management	**Medium** May require new machinery and guidance equipment	**Low** No direct impacts expected	**Low** Reduced likelihood of diffuse nutrient pollution.	More sharing of knowledge to identify both the benefits and limitations for different farming systems Lack of independent advice /information on the suitability of different approaches

Table 11 -continued

Land management measure	**Rationale for adoption on farm**	**Practicability (high/ medium / low)**	**Implementation cost (high/ medium /low)**	**Expected benefit for soil biota (high/ medium/ low)**	**Expected benefit to wider environment (high/ medium/ low)**	**Issues and constraints affecting widespread adoption in the UK**
Use of plants to provide herbicide or biofumigation effects	• To reduce weed germination • Allelopathic effects • To reduce beet cyst nematode	**Medium** May be adopted as one measure where pesticides or sterilisation reduced	**Medium** Increased seed and management cost for additional crop	**Low/ medium** Aim is to affect community structure hence may be a mix of negative and positive effects	**Low** May allow reduced use of pesticides and/or sterilisation Often also used as catch crops	Some on-farm use and demonstration (especially mustard), but little evidence of impacts to guide more widespread adoption
Application of Plant Growth Promoting Rhizobacteria or Fungi	• None; practice largely unknown by farmers	**Low** Not readily used at field scale in the UK	**High** Costs very high as materials not readily available. May need specialised application equipment	**Low** Very limited field evidence Some positive benefits recorded by research trials under controlled conditions	**Low** Little study of wider ecosystem implications	Farmers lack knowledge and understanding Research on-going but may be more applicable to high value crops/ controlled conditions
Application of molasses based stimulants for microbial activity	• Quick stimulation of microbial activity • To increase crop residue or manure breakdown	**Medium** On-farm may be co-applied with other sprays (pesticide. herbicide)	**Medium** Information on cost effectiveness not readily available	**Low** Very short –term stimulation of activity – especially bacteria	**Low** Would have to be applied in very large quantities to have any observable food chain effects.	Widespread use as silage stimulants. Some on-farm use and demonstration but little evidence of impacts

Table 11 -continued

Land management measure	Rationale for adoption on farm	Practicability (high/ medium / low)	Implementation cost (high/ medium / low)	Expected benefit for soil biota (high/ medium/ low)	Expected benefit to wider environment (high/ medium/ low)	Issues and constraints affecting widespread adoption in the UK
Application of gypsum	• Liming • Source of Ca and S • To improve soil structure	**High** Applied as fertiliser / lime or can be mixed with manures	**Medium** Material not high cost. Claims of widespread benefits but little independent evidence; difficult to assess cost-benefit	**Low** No evidence of direct benefits for soil biota.	**Low** Where soil structure is improved – reducing sediment loss	Used to stimulate structure formation and stabilisation Some on-farm use and demonstration; befits associated with saline soils

4.1 Increasing the amount, and managing quality, of OM inputs

On-farm practices that increase the amount and manage the quality of OM inputs generally have positive benefits for soil biota, with expected enhancement of, or low risk to, other soil functions and the wider environment. Impacts are driven by the increase in energy and nutrient sources for the soil food web and hence are broad-scale with increases in both biomass and activity of all soil biota groups commonly measured. Changes in the community structure and composition of soil biota are recorded less commonly and seem to be driven by the quality of the OM inputs (C:N ratio etc.). Evidence to date does not indicate that increased OM inputs (resource availability) lead to reduced diversity of soil biota (within the likely range of increases that are achievable in practice), possibly due to an interaction with the contemporaneous increase in niche differentiation within the soil habitat .

In livestock systems, on-farm management changes to manure handling with reduced direct use of slurry and more on-farm composting provide an opportunity to enhance soil biota; similar changes are separately recommended as part of water protection measures. Positive benefits of changes in manure handling seem to accrue largely as a result of the reduced negative effects of slurry application.

Fewer opportunities exist for on-farm management of OM inputs for arable and horticultural crops, but where crop residues are routinely incorporated, benefits for soil biota are seen. In arable and horticultural systems, repeated regular applications of waste OM (local and composted), e.g. green waste compost, mushroom compost, paper waste, coffee grounds, have been shown to have significant benefits for soil biota. The greatest limitation to increased uptake of such OM imports and their application seems to be the availability and cost of materials.

Where particular materials (seaweed, biochar) are promoted more widely as inputs, they should be assessed with due care in relation to all aspects of soil function; there is currently no evidence that these particular OM sources provide any additional benefit to soil biota, beyond that of an energy/nutrient source as described above. Farmers have become used to the concepts of nutrient management planning and nutrient budgeting for their fields and farm – similar concepts applied to OM would be likely to promote considered use of OM within the farm and to more rapidly identify farm requirements for OM import. Development of integrated waste management solutions in the wider community such as promoted by WRAP may be needed to support long-term availability of OM inputs from off-farm to farmers.

More work is needed to assess whether there are specific benefits of composting OM inputs as part of an integrated strategy to manage soil-borne disease, as well the role of composts as soil conditioners to maintain soil OM content and soil structure. There is no evidence that it is possible at farm scale to develop tailored composting methodologies that deliberately target specific components of the soil biota or particular soil functions by controlling the quality of the OM inputs to soil. Such an approach would also need to consider how farmers could robustly assess the requirements within their system to target specific components of the soil biota. Currently there is limited evidence that such interventions give significant benefits above those resulting from increased OM inputs from composted materials.

4.2 Reducing intensity of tillage practices

Reduced tillage intensity with limited use of inversion tillage shows benefits for soil biota. However, these seem to be direct effects only for soil macrofauna; more generally the impacts are mediated through increases in the amount or changes to the quality of OM inputs or changes in plant diversity. Action to encourage famers to reduce tillage frequency and intensity would carry low risks and, besides benefitting the soil biota and their function, would also reduce fuel usage.

More work is needed to assess changes in tillage approaches already adopted within farming systems on soil biota and soil function e.g. the use of aeration within the grassland systems. Where such tillage approaches are adopted together with changes to management of OM inputs, e.g. by application of composted manures immediately following an aeration pass, it seems likely that additional benefits will accrue for both soil biota and soil function. However, the outcomes of such combinations of management are relatively little reported in the literature. Conservation agriculture approaches (no-dig for horticulture and no-till for combinable crops) seem to lead to measurable benefits for on-farm ecology both above and below–ground as a result of reduced tillage intensity coupled with larger OM inputs. More work is needed to assess whether the benefits of these systems outweigh the costs, agriculturally and environmentally. Where no-till or no-dig systems are already applied, these may also allow monitoring of impacts on soil biota and wider soil function (e.g. impacts of GHG emissions and agricultural pests) using paired farm approaches. Farms or fields on farms could be selected in a way that explicitly accounts for soil, landscape structure etc. but where different tillage approaches have been applied. This type of paired farm approach has been used to examine impacts of agricultural practice on above–ground biodiversity and was pioneered for studies of bird populations (Chamberlain *et al.* 1999).

Some crops, especially large–scale root and vegetable crops, are associated with extremely intensive tillage; there is almost no work on approaches to reduce tillage in these systems. The targeted use of OM inputs has been observed to increase soil structural and biological resilience thus allowing sustainable use of intensive tillage rotationally; however, this has also been little studied. More work is needed to understand the role of OM and soil biota in the resilience of soil functions, including but not only with regard to mitigating the impacts of tillage.

4.3 Diversifying cropping systems

In arable and horticultural systems, diversification of crop rotations compared with monoculture or minimal break crops and/or the integration of green manures (including cover crops) into crop rotations have positive benefits for soil biota. Increases in crop species diversity within a rotation are often associated with an increase in measured species richness within the soil biota. In the future, cultivar selection may also provide a tool to manage soil biota through selection of varieties with different affinity for AM fungal associations or different patterns of root exudation; the data to support such selections is not yet routinely available.

Increases in the biomass and activity of soil biota are commonly measured where rotations include cover crops even if there are no other changes to the rotation. However, relatively little work has been carried out on the impact on soil biota of the use of green manures within rotations, let alone specific advice on the most appropriate green manures for any soil/ rotation combination and the most appropriate management of them (cutting/ grazing regimes etc.). Nonetheless green manures/ cover crops have been used in practice for a number of years, so that farmer understanding of practical combinations is increasing. These practical applications may also allow additional monitoring of impacts on soil biota and wider soil function through a paired farm approach such as that highlighted for comparing tillage practices.

Green manures, cover crops and grass leys provide opportunities for increasing OM inputs to the soil in situ. In natural ecosystems, net primary production is often strongly linked to the biomass and activity of the soil organisms. In 'conventional' agricultural systems, plant breeding has focussed on increasing the biomass of the marketable component (e.g. grain, fruit) at the expense of crop residues, hence limiting or reducing inputs of OM to the soil. A combination of rotational planning (exploiting the benefits of plant diversity in space and time) and plant breeding approaches (both to manipulate rhizosphere inputs, and to increase amounts or manipulate quality of residues) may overcome potential constraints to the soil OM balance due to the availability and cost of OM imports. In situ plant sources of OM inputs represent true additional carbon and may also allow the increased organic matter inputs required to be sustained over decades.

Within livestock systems and mixed farming systems, diversification within forage crops and in grazed swards may be an important tool to increase on-farm plant diversity. Whole-crop silage is increasing in extent and species mixtures are increasingly common including legumes to increase forage protein levels and reduce N fertiliser requirements. Mixed species swards may address a number of farm objectives including fertiliser reduction and improvement in livestock health; hence there is a range of farmer experience following implementation that could be shared. However, there is currently little field evidence or demonstration to aid in on-farm mixture selection or to investigate the impacts on soil biota of particular mixtures. Additionally, the impact on soil biota of grazing management strategies (including the balance between cutting and grazing management or the impacts of different temporal/spatial patterns or duration of grazed/ungrazed periods) have not been studied. Such changes are very likely to lead to significant differences in energy and nutrient fluxes between above and below-ground ecosystems, hence it would be useful to establish whether grazing/cutting management has impacts on soil biota and hence whether it might be used as a tool in future within livestock systems to enhance soil biota (biomass, activity, diversity) or associated soil function.

The benefits for soil biota accruing through crop diversification are strongly linked to the associated changes in OM inputs through roots and crop residues and tillage patterns resulting from changes to the cropping system and/or rotational pattern. It seems likely that the integration of tree crops within arable and livestock systems would also have significant benefits; there is some research evidence confirming this but little practical farmer experience. Integration of lignin rich/woody crops into farming systems as energy crops may provide an opportunity to further consider agroforestry approaches.

4.4 The opportunity for point interventions to enhance soil biota

The most common interventions in agricultural systems are the use of fertilisers and pesticides. Laboratory studies usually only consider impacts of single agrochemicals, and more work is needed to assess the combined effects of typical pesticide and fertiliser regimes in the field. The few field-based studies looking at normal field application rates suggest that there is relatively little direct impact of fertiliser or pesticide on soil biota in terms of biomass, activity or diversity. Consequently point interventions to reduce or target fertiliser or pesticide use are expected to have relatively little impact on soil biota. More work is needed to confirm the low impact of pesticide and fertiliser regimes in the field; however, it is clear that Cu-based fungicides as used within some organic farming systems can have significant cumulative and long-term impacts on soil biota.

Within intensive horticultural systems (tomatoes, strawberries) the use of soil fumigants is still common, while the most common chemical (methyl bromide) has been phased out, alternatives are used. Repeated soil sterilisation can lead to very significant reductions in biomass and activity of the soil biota and changes to community structure. Hence wherever possible the use of general purpose soil fumigants and/or sterilisation should cease. The change to the soil biota may not be remedied simply by ceasing regular sterilisation. In these very intensive cultivated soils, remediation by addition of composts or inocula may be possible, but no research has been done to confirm this. Such instances are very rare outside controlled cropping.

The project also considered a number of proposed specific practices often targeted at individual species or functional groups within the soil biota. These point interventions directed at soil life, such as the use of compost tea or a microbial inoculant, have largely been developed and studied in controlled conditions and are currently used by small number of farmers. Where such interventions have been adopted on-farm, they usually form part of a set of changed practices, which include a range of system-oriented changes to the management of OM inputs and tillage. Robust data on the distinct effectiveness of most point interventions under field conditions is therefore not available. As discussed above, such system-oriented changes are likely to have broad-scale benefits for soil biota, with increases in both biomass and activity of all soil biota groups measured. Hence optimising system management is also likely to increase the effectiveness of the indigenous soil micro-organisms, including AM fungi, in plant growth promotion. Field data that are available of the effectiveness of point interventions suggest that the method of application, carrier etc may have as significant effect as any microbial inoculant. Inoculation of specific crops/varieties with targeted rhizobia / mycorrhizal fungi is warranted where the association is obligate – however, this appears to have relatively little direct impact on the indigenous soil biota. More general use of AM fungi inocula has been proposed; evaluation to date suggests little effect, but on farm trials may provide an opportunity to evaluate this (and other practices such as use of compost tea) more fully.

4.5 Constraints to adoption of practices to enhance soil biota

For most farmers the first step in uptake of land management practices likely to enhance soil biota is an explicit acknowledgement of soil biological fertility as a key part of the system. Although increased attention is now paid to the role of the soil biota in soil function in the scientific literature, there is much less awareness of the topic and engagement with it amongst farmers and advisors. Consequently this research found that there is a need to present messages about soil management delivered to farmers to address physical, chemical and biological aspects of soil in an integrated way together with their relationships to sustainable agricultural production. In the first instance, targeted information and training for on farm advisors actively engaged in giving soil management guidance will have the greatest impact; materials developed for this purpose can then be made available widely.

Workshops with farmers currently at the forefront of developing techniques to enhance soil biota showed that they were prepared to take up practices which required more of their time and may also have required significant capital investment where they had been convinced of the long-term need and business benefit. However, even these farmers asked for more, particularly more information and tools that could support them to make more effective decisions for their farming system and evaluate the impact of practices in place.

In particular they felt that while farmers are able to make use of tools to measure soil chemical conditions (pH, P, K) they are not currently well equipped to make decisions that take soil biota into account. While there remain limitations to the techniques currently available for measuring soil biota and their activity, it seems to be timely to consider how such approaches could be rolled out to provide an assessment tool for soil biota (and biological fertility) which is accessible to farmers. This would complement monitoring of soil quality more generally and could be integrated into existing farm advice streams

Farmers recognised that constraints to adoption of untried practices included the lack of information / advice and /or a lack of access to it. Farmers felt that for most practices there was a lack of robust independent information about the effectiveness, other implications, cost and benefits of the land management practices considered. Many of the practices were used for several reasons, which might include economic or management drivers as well as reflecting a concern for soil biological function. In many cases, a lack of independent information, against which the recommendations of salesmen can be cross-checked, is limiting uptake and in some cases may be promoting uptake of suboptimal practice that may work against or fail to achieve the farmer's objectives.

The project demonstrated that there was already significant experience within the farming community in systems and practices that are likely to enhance soil biota and soil function. Consequently mechanisms that promote the sharing of knowledge through farmer-farmer learning are likely to be effective; similar informal mechanisms have developed for sharing of best-practice on no-till. Where possible, such informal learning opportunities should be supported through practical demonstration not only of single practices but also how to integrate effective enhancement of soil biota within everyday farming practice. These assessments should ideally include a full cost-benefit analysis together with observations of impacts on product yield and quality, alongside the implications for the soil biota.

Table 12 Recommended practices to maintain and enhance soil biota (amount, according the main farming enterprise; approaches worthy of further consideration also given in italics

Main enterprise	System-oriented approaches			Point interventions
	Increase OM inputs	Reduce tillage intensity	Increase plant diversity	
Horticulture	• Repeated regular applications of crop residues and local waste OM (composted) • *Vermicomposting*	• Minimum intensity tillage; limited use of inversion • *No-dig/ mulching approaches*	• Integration of green manures • *Intercropping approaches* • *Permaculture*	• Ceasing use of soil fumigants / soil sterilisation
Arable	• Repeated regular applications of local waste OM (composted)	• Minimum intensity tillage; limited use of inversion • No till/zero till (cereals and oilseeds)	• Diversification of crop rotations compared with monoculture or minimal break crops. • Integration of green manures • *Bi-cropping cereals and legumes* • *Intercropping / agroforestry*	
Dairy	• Mixed methods for on-farm manure handling - reduced direct use of slurry and increased composting	• Overseeding approaches	• Diversification of crop rotations with grass/clover leys • Mixed species swards for grazing and conservation • *Bi-cropping cereals and legumes for whole-crop silage* • *Agroforestry*	
Grazing livestock (beef/sheep)	• More effective on-farm composting of manure	• Overseeding approaches	• Mixed species swards for grazing and conservation • *Agroforestry*	

4.6 Conclusions

This research demonstrates that there are clear opportunities for farmers to maintain and enhance soil biota to support agricultural production and provide environmental benefit. The broad scientific understanding of soil biota management is now at a stage where active management to improve the biomass, activity and diversity of soil biota can be encouraged, and the general principles underlying the management practices required have been clearly identified in this report. Farming that seeks to takes advantage of biological activity in the soil should aim to increase and diversify organic matter inputs to the soil, reduce soil disturbance, and seek to maintain a spatially and temporally diverse cover of plants as forage, crops or green manures. In addition to these broad general principles, specific management practices have been identified which can be recommended for their soil biological, and wider environmental, benefits, practicality and low risk of adverse impacts. These are summarised in Table 12 above with reference to the broad farm enterprise type to which they are most applicable. , It is expected that these will be combined and adjusted for the site according to constraints due to soil type and/or local climate. Many practices have wider environmental benefits, such as additional soil carbon sequestration, enhancement of above-ground biodiversity, improvement to soil structure, or increased duration of land cover, which will help to reduce diffuse pollution to water courses. For many of these practices there is a barrier to farmer uptake, with a recognised need for clear and quantifiable demonstrations of their impacts on soil biology, and benefits and costs to agriculture and the wider environment.

A number of further practices are also highlighted within the report as potentially beneficial to the soil biota .However, progression in these areas to establish whether the practices should be recommended for farm uptake will require some directed research in particular we recommend research that considers:

- whether there are specific benefits of composting OM inputs for the management of soil-borne disease as well as maintenance of soil OM content and soil structure;
- whether targeted use of OM inputs can confer resilience to soil functions mediated by the activity of soil biota;
- whether rhizosphere inputs to stimulate targeted soil organisms (e.g PGPR, AM fungi) can be manipulated through crop variety selection or crop management (grazing/ cutting etc);
- how in situ carbon inputs can be maximised through the use of green manures, cover crops and leys rotational planning and crop/variety selection to overcome current constraints to the soil C balance;
- how intercropping and/or agroforestry approaches can be integrated most effectively into UK farming systems; and
- the added value of point interventions, such as compost tea or general microbial inoculants, against a background of effective system level management where soil biota are maintained and functioning at a high level.

Effective uptake of practices that maintain and enhance soil biota to support agricultural production and provide environmental benefit will also be progressed by ensuring that measurements of impacts on the ecology and function are integrated into the suite of soil and productivity variables measured when evaluating impacts of management change. This will not only generate a better understanding of management impacts on soil biota, and how to mitigate these, but will also contribute to a better functional understanding of how soil biota can contribute to developing more sustainable and productive agriculture.

Where there is sufficient understanding of the efficacy of practices to increase beneficial soil biological functions, there remains a challenge to develop effective knowledge transfer. This project has identified knowledge transfer requirements relating to the practices in the sections above. One key requirement identified is a set of tools and standards that farmers can use to measure and evaluate soil biological health on their farms. However, uptake of these approaches by farmers is likely to be balanced against the cost of adopting the techniques, which may be best evaluated through use of carefully monitored demonstration farms, and through evaluation of the performance of paired farms.

The role of soil biota in supporting food production was increasingly marginalised with the intensification of farming systems during the 20th century (Giller *et al.* 1997). However, opportunities for agro-ecological intensification are likely to become increasingly cost-effective as input costs continue to rise (diesel, pesticides, fertilisers). Some farmers have already adopted these practices in conventional and organic and for arable, livestock and horticultural systems (Appendix 4). Therefore there is significant potential for wider adoption of such practices to enhance soil biota and increase the complementarity of measures adopted for other reasons with the enhancement of the ecology and function of the soil. Where possible, the adoption of such practices should be highlighted in current advice streams providing training and information on soil management.

There are clear benefits to ensuring good soil biological health for both agriculture and environment. Widespread adoption of farm practices guided by the general principles identified in this report will be needed to secure these benefits. To encourage adoption it will be necessary to progress research into specific practices identified above. Demonstration farms, with comparisons to standard practices, will help to communicate the benefits of working with the soil biota, but must be well-supported by scientific monitoring to demonstrate and quantify the costs and benefits. Bringing soil biological testing into the mainstream will enable farmers to determine how successful their management changes have been. To encourage behaviour changes, available ELS/HLS options could be compared with the general principles identified here and, if necessary, new options developed to encourage systems-oriented approaches that encourage the activity, biomass and diversity of the soil biota. In all cases, this future activity must be integrated with existing farm advice streams.

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APPENDIX 1 – Effectiveness of key agricultural practices and systems considered to enhance soil biota – a critical review of the literature

1.0 Background – concepts and framework underpinning consideration of the links between agricultural management and soil biota.

The potential use of land in any location is rarely unconstrained. Assessment of land use quality uses a number of relatively fixed site characteristics to define the quality of land (e.g. climate, slope, some soil factors). These site factors are largely unmanageable and consequently they set the boundary for the range of agricultural practices that are possible. For example, in the Agricultural Land Classification system used in England, land of Grade 5 is not suitable for cultivation, whereas it would be unusual for land of Grade 1-3a not to experience at least some rotational cropping with arable or horticultural crops). Similarly a number of fixed site characteristics (climate, depth, stoniness, mineralogy, texture) have been used to define the *maximum potential* soil organic matter (OM) content , where the actual soil OM content is then determined by interaction with land management (Ingram and Fernandes 2001; Dick and Gregorich 2004). Hence the identification of agricultural practices and systems which will enhance soil biota will also needs to take into account the underlying combination of fixed site characteristics; there is potential for some sites always to have greater size, activity and diversity of soil biota than others.

Fixed site characteristics provide a template within which organisms and ecological systems operate. The architecture of the soil pore network largely describes 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 not only on soil texture but also on the aggregation of mineral particles and soil OM i.e. the formation and stabilisation of soil structure. Soils contain pores of a range of sizes, which across the typical range of soil moisture contents may be air-filled (large transmission pores), water-filled (very small residual pores) or contain varying amounts of air and water (storage pores, intermediate in size). Many soil organisms are also dependent, on the presence and continuity of water films; as soil water content decreases the frequency of encounter of soil organisms also reduces e.g. predation of bacteria by protozoa and nematodes has been predicted from soil water content and pore geometry (Young and Crawford, 2001). Soil structure is not a fixed property, however, and is modified as a result of the activity of soil organisms (e.g. Beare *et al.* 1995; Lavelle, 2000; Rillig *et al.* 2002).

Available food resources are also a key factor in determining available habitat for any species. In general a close relationship has been shown between soil OM contents and the size of the soil microbial biomass pool (Wardle 1992), and the “attainable soil microbial biomass” for any particular land-use system can be defined by a combination of site factors and those controlling the inputs of organic C to soil (Gonzalez-Quiñones *et al.* 2011). In natural systems, the nature of the plant community determines both the amount and types of carbon (C) inputs to soil via root exudates, roots and residues and provides opportunities for direct plant-microbe associations; above and below-ground diversity are therefore linked

(Wardle 2002; Swift *et al.* 2004; Sylvain and Wall, 2011). Plant root systems are a key habitat for a number of soil organisms, including symbiotic bacteria, mycorrhizal fungi, plant pathogens and herbivores. The root surface (rhizoplane) and the zone of soil surrounding the root within which the soil is directly affected by the root's presence (rhizosphere; Killham, 1994) can be distinguished from bulk soil by changes in chemical and physical properties and both are associated with communities of soil biota that are distinct from those in bulk soil (e.g. Griffiths et al., 1999; Marschner *et al.* 2001).

Populations of soil biota are adaptive to changes in environmental circumstances in a way which the physical environment is not (Kibblewhite et al. 2008). Hence, describing and modelling soil processes which result from the interactions of soil biota with each other and with the soil environment is often caught in the "middle number" conundrum i.e. there are too many individual components with too many complex interactions to deal explicitly with the individual; yet the individual details affect the dynamics of the system as a whole, so general statistical properties yield an incomplete picture of the activity of the soil biota (Wu and David 2002). This problem is amplified by spatial and temporal variations and interdependencies, scale dependencies and thresholds. It is also clear that organisms' response to the physical environment may exhibit patterns that vary between species and are constrained by the geometry of the environment (Williams *et al.* 2002); differences in species size and mobility lead to differences in the species/habitat interaction (Giller *et al.* 1997). Fitter (2005) therefore suggested that "meta-population ideas are necessary or possibly even meta-community or meta-ecosystem approaches" to cope with the heterogeneity of soil. Soil can be therefore be conceptualised (using approaches from landscape ecology) as a series of linked habitats for soil biota where soil functions (which result from soil processes) are the outcome of the interaction of soil habitats and populations strongly influenced by the spatial context. These interactions can be defined as *per* Wiens (1992) in terms of: i) composition i.e. which habitats are present and their amount, quality, stability characterised by patch measures; ii) structure i.e. how habitats are arranged in space, boundaries, permeability, stability of arrangement characterised by mosaic measures, and; iii) flows i.e. how habitats are linked through time by movements of individuals, energy, water and nutrients.

The focus of this review is on the effectiveness of key agricultural practices and systems considered to enhance soil biota. Hence it is important, in addition to the role of fixed site factors, to consider how the additional impacts of a range of land management practices and other natural disturbances (e.g. fire) on the soil biota can be described. Such disturbances have both direct (through physiological effects on populations) and indirect effects through impacts on soil habitats and/or other organisms. A simple schematic model (Figure A1) developed by Stockdale et al. (2006) shows how soil processes are the outcome of interaction between soil habitats and the populations of soil biota and how these interactions are affected by both fixed site factors and disturbance factors. In much of the literature, impacts of agricultural management practices on a species, soil process or soil property are measured separately, we will use this simple model to provide a framework for integrating findings from different studies and drawing out general principles.

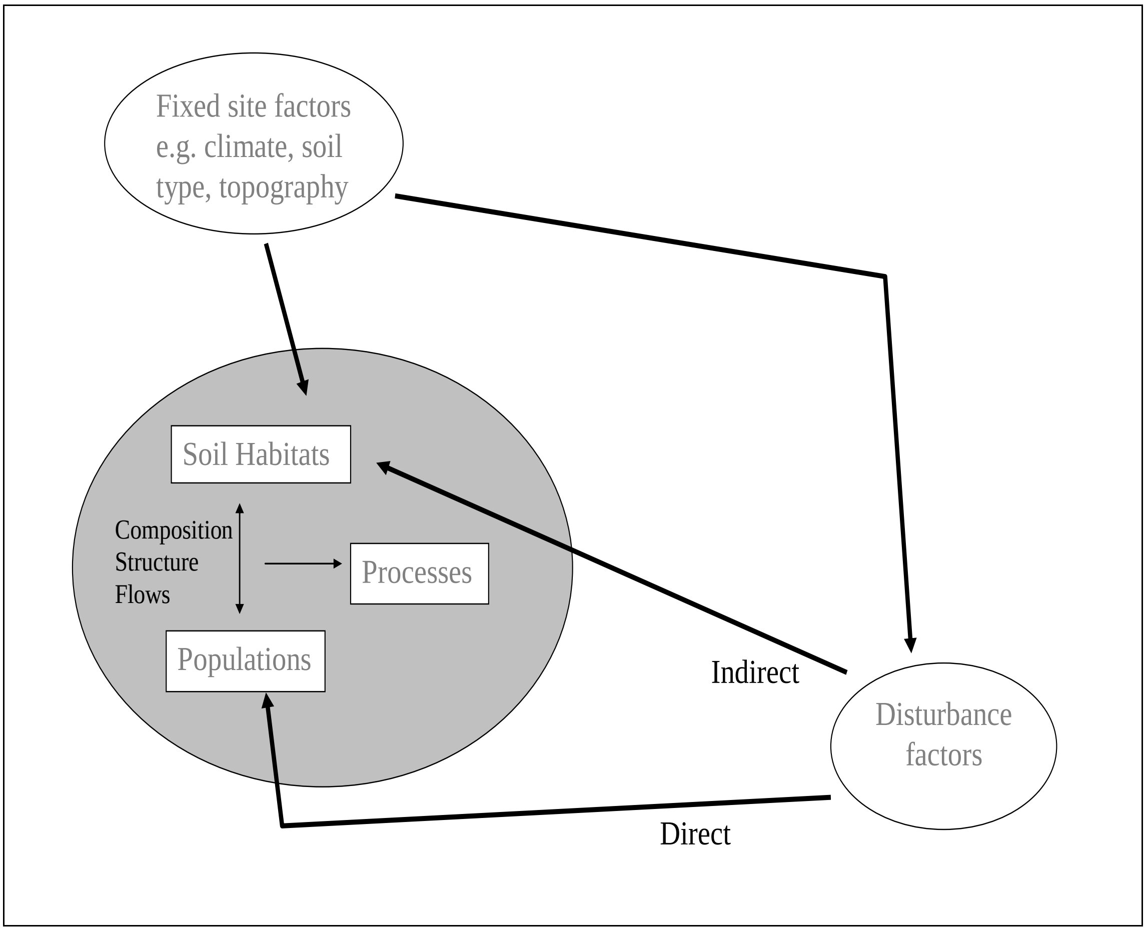

Figure A1 Simple schema showing the interaction of fixed site and disturbance factors in their effect on populations of soil biota and soil processes which are considered to result from the interactions between soil habitats and the soil biota (Stockdale *et al.* 2006)

The focus in the literature review has been on recent developments (2006 – 2010) to allow the review reported in Stockdale et al. (2006) to be updated with a particular focus on the impacts of common practices within UK farming systems. The evidence of impacts of agricultural practices on soil biota is largely derived from either i) observed impacts of long-term differences in systems (where a number of practices have changed) e.g. comparisons of organic vs conventional farming systems; snapshots of woodland vs grassland vs arable systems or ii) short term monitoring of changes in a single practice e.g. additions of manure; comparisons of differences in tillage intensity with no changes in crop residue management or variety choice. Increasingly more complex systems with interactions of common management practices are being studied e.g. Overstreet *et al.* (2010). We have applied a structured grouping of agricultural management practices in terms of the scale of their impacts on soil biota (Defra 2010) i.e. i) systems-oriented approaches that provide energy-containing substrates and/or seek to optimise soil habitat, as distinguished from ii) those that target specific often monotonic aspects of the soil biota or their environment (= point interventions) such as biocontrol, inoculation with specific species (mycorrhizal fungi, rhizobia) or mixed species cultures (plant growth promoting rhizobacteria, PGPR).

The evidence base used here derives from a number of scientific studies employing a range of methodologies. This often makes direct comparison of the results of different studies difficult. For example Bardgett et al. (1999a) used fumigation extraction methods to determine soil microbial biomass and phospholipid fatty acid extractions to determine the abundance and ratio of bacterial and fungal biomass. Differences in seasonal trends (fumigation extraction showed summer maxima and winter minima in biomass; in contrast PLFA measures had spring maxima and autumn minima) highlighted that the methods may detect different microbial biomass pools, with PLFA detecting the active proportion alone. Also Smith et al. (2001) used both culturing and molecular approaches to study soil bacterial populations and measured different patterns of response both seasonally and to the agricultural practices studied; again these methods detect different microbial biomass pools. Hence account needs to be taken of the methods used as well as the results obtained in comparing between studies.

It can also be difficult to distinguish direct and indirect effects of land management practices from data collected in the field; consequently many of the studies reviewed here provide a report of the net result of both. Seasonal dynamics of below-ground populations in response to the dynamics of temperature and water are often not taken into account in studies comparing agricultural practices. These changes may have greater effects on populations than farming practice e.g. Spedding *et al.* (2004) observed larger seasonal variations in fungal and total microbial biomass content than those linked to the tillage or residue management treatments. Consequently care needs to be taken when comparing data collected in different ways, at different times of year and on different sites.

In the report presented here, the focus is on summarising and presenting information from the literature on the impacts of agricultural practices on the biomass, activity and diversity of the soil biota. Much of the literature focuses on the likely impacts of agricultural practices (mostly negative) on the soil biota. The approach in the following review has therefore been to look for key principles and points of general agreement rather than to carry out a full and rigorous meta-analysis. In the main report the information presented here is integrated and evaluated to consider the potential of agricultural management practices and systems in enhancing the function, and diversity, of the soil biota and the likely impacts on soil function for agriculture and other ecosystem services.

2.0 Impacts of systems-oriented agricultural practices

2.1 Grazing management in lowland and upland agricultural grasslands

Grazing i.e. the above ground defoliation of grass and forb species by herbivores typically consumes up to half the annual above ground net primary productivity, but also involves deposition of dung and urine and often trampling of the soil. The rate and extent of defoliation in agricultural systems is largely controlled by livestock management practices particularly grazing duration and stocking rate. In the long-term grazing is also a key factor is driving the composition of vegetation community, particularly in semi-natural systems. Defoliation has been shown to reduce the amount of root exudation with consequent reductions in the activity of the cultivable soil bacterial population (Macdonald *et al.* 2004). Other studies have shown increases in root exudation following defoliation (e.g. Hamilton and Frank 2001). However, other impacts of livestock, including trampling effects potentially leading to compaction and the returns of dung and urine to the soil surface, confound the direct impact of defoliation in any assessment of grazing management strategies. Supplementary feeding of livestock during the grazing period may also significantly increase inputs of C and nutrients to the below-ground ecosystem via excreta. These combined effects therefore mean that grazing affects the amount and quality of C (and other nutrient) input to the soil in quite a complex way (Bardgett *et al.* 1997). Neilson *et al.* (2002) showed that grazing had a significant impact on trophic interactions below ground and consequently on C and N cycling.

Overstocking even for short periods has negative impacts, which probably arise due to increased compaction, poaching, disruption of the sward and an increased proportion of bare ground in overstocked swards. For example, where soil bulk density increases as a result of compaction, AM fungal colonization has been shown to decrease (e.g. Entry *et al.* 1996, Jirout *et al.* 2009). Research in Ireland has also shown a negative correlation between % cover of bare ground (caused by poaching) and carabid species richness in grazed swards (Ni Bhriain *et al.* 2002). Increased urine returns in overgrazing situations may interact with poaching to exacerbate the impacts on soil biota and soil processes. Urine stimulates soil microbial turnover (Petersen *et al.* 2004) and in a study of the effects of excretal returns and soil compaction on nitrous oxide emissions Simek *et al.* (2006) has recently shown high levels of available C, high microbial biomass and pH associated with the areas most severely affected by livestock.

General relationships between stocking density and soil biota (Table A1) are modified depending on the typical stocking density of the system. Where stocking rates are already high (> 1.0 livestock unit per hectare) such as typically seen in lowland grassland, increased stocking rates are usually associated with negative impacts (Mulder *et al.* 2003). A field experiment with increasing grazing pressure by sheep in natural grasslands demonstrated that collembolan abundance increased with grazing pressure, but species diversity decreased; some species increased in abundance while others were greatly reduced (Dombos, 2001). In upland grasslands, increased stocking can increase plant growth and lead to changes in the vegetation community due to increased nutrient cycling and hence increase soil biota biomass, activity and diversity (Yeates *et al*. 1997).

Table A1 Summary of grazing impacts on below-ground organisms updated from Stockdale *et al.* (2006)

Species/group	Average impact of increased grazing intensi	Key references
Bacteria and archaea	Significant increase in nutrient limited pastures due to stimulation of exudation and increased nutrient returns through excretion.	Yeates *et al.* 1997
Fungi	Decline in response to increases in grazing intensity; increases in nutrient limited pastures due to stimulation of root growth, exudation and residue returns	Klummp *et al.* 2009; Wakelin *et al.* 2009
AM fungi	Reduced if overgrazing causes compaction	Entry *et al.* 1996
Nematodes	Significant reduction in biomass and reduction in species richness along a gradient of increasing grazing intensity	Mulder *et al.* 2003
Collembola	Reduction in species richness in fields higher grazing intensity	King and Hutchinson 1976; Dombos 2001
Earthworms	Little to no impact, slight increase with grazing intensity	Hutchinson and King 1980; Muldowney *et al.* 2003
Insects	No impact or reduced by grazing	Ni Bhriain *et al.* 2002; Macaulay Institute 2006;

In a transect of lowland grasslands Mulder *et al.* (2003) showed a decline in species richness and the biomass of most nematode species in grassland as the number of livestock units per hectare increased (a measure of intensification); several bacterial feeding nematodes showed no sensitivity to increased livestock density and two nematode species showed a reverse trend and increased with increasing livestock density (the bacterivore *Chiloplacus* across the whole gradient and the carnivore/omnivore *Thonus* under semi-intensive and intensive management). These patterns are similar to those shown by Ferris et al. (1996) in a comparison of conventional and organic grasslands. Schon *et al*. (2008) showed similar changes in mite communities (oribatids) with a decrease in diversity and abundance, and shifts towards reduced fungivores, and increased omnivorous species. Parfitt *et al.* (2010) also showed that increased intensity of grassland management was associated with greater numbers of bacterial feeding nematodes which suggests a shift from fungal to bacterial pathways with increasing intensity; this may lead to soil microbial/microfaunal interactions that retain less of the reactive N within the soil microbial biomass, with a consequent greater risk of N loss. Klummp et al. (2009) studied the impact of changes in (simulated) grazing intensity on pastures that had reached equilibrium under high or low grazing intensity. Within 18 months intensification of grazing intensity led to changes in grass species and a shift from fungal to bacterial pathways of decomposition with bacterial release of previously stable C and increased N losses; in contrast no changes to the soil bacterial or fungal community were measured over the same period when grazing intensity was reduced. The 'recovery' of a fungi-dominated soil microbial community, where grazing intensity is reduced, may therefore be much slower than the established of a bacterial-dominated microbial community when grazing is intensified.

Veterinary medicines include a variety of nematicides, hormones and anti-microbials, which may impact on below-ground ecology as a result of deposition in grazing excreta or through application of manures. Direct application of anti-microbials and nematicides usually used as veterinary medicines to soil has a negative impact on soil microbial populations and impacts below-ground food webs (Westergaard *et al.* 2001; Svendsen *et al.* 2005; Jensen *et al.* 2003). There is some evidence of reduced numbers and activity of dung beetles and other insects where veterinary drugs are used regularly (Hutton and Giller 2003) and retarded decomposition rates of dung are likely to have an impacts on other species.

There is almost no literature which reports the impact on soil biota of integrated grazing management strategies including the balance between cutting and grazing management or the impacts of different temporal/spatial patterns or duration of grazed/ungrazed periods. In one of the only reported studies Mills and Adl (2011) showed no difference in nematode species richness or body size due to a range of grazing management systems in Nova Scotia; season had a much larger impact than differences in the grazing systems used. Studies on grazing impacts usually compare arable and grazed land, grazed and ungrazed land or grasslands managed at different stocking rates (grazing intensity). Overall, data suggest that lowland grassland with lower grazing intensity (associated with lower fertiliser application or organic farming systems) have increased biomass and particularly diversity, of soil biota. However, the limited number of studies which have studied reductions in grazing intensity as a deliberate management practice have found no/ only slow changes in the biomass and diversity of soil biota.

2.2 Tillage

Tillage is the manipulation, usually mechanical, of soil properties to modify conditions for crop production. Most tillage operations decrease soil density in the disturbed zone and practices can be grouped into those which invert, loosen, mix or crush the soil. It is critical to recognise that the resultant soil properties following any tillage operation, even where the same implement is used, depend on a combination of equipment factors (including depth, energy input, speed) and soil factors (including water content, texture, residue cover). Consequently "it is difficult to visualise, let alone predict, the soil conditions resulting from a given operation" (Unger and Cassel, 1991). Tillage may also incorporate crop residues, fertilisers or other amendments. All of these operations are often combined within a single tillage operation in the field. However in the following section the effects of soil disturbance through tillage will be considered alone.

The largest differences in the biomass, activity and diversity of soil biota are seen between permanent grassland (never tilled) and arable systems; however, increasing tillage intensity such that resulting from the inclusion of potato crops in an arable rotation also has significant but small additional negative impacts e.g. on nematode populations (Postma-Blaauw *et al.* 2010). Wardle (1995) carried out an extensive review of the impacts of disturbance through tillage on food-webs in agro-ecosystems. The conclusions of his meta-analysis show that tillage tends to reduce large soil organisms (beetles, spiders, earthworms) more than the smallest ones (bacteria, fungi). On average some intermediate-sized groups such as bacterial feeding nematodes, mites and enchytraeids even show small population increases probably due to changes in the populations of their prey species (Table A2). Postma-Blaauw *et al.* (2010) also showed larger immediate impacts on the abundance and diversity of taxonomic groups with larger body size (earthworms, nematodes enchytraeids, and microarthropods) than smaller-sized taxonomic groups (protozoans, bacteria, and fungi) whether converting arable to grassland (positive impacts) or grassland to arable (negative impacts). Tillage impacts are larger on larger organisms. For example, McHugh et al. (2009) showed that the density of macropores was increased by 50% in the first 10 mm of soil where a combination of no-till and controlled traffic systems was used as a result of increased earthworm biomass and activity.

Despite limited evidence, a reduced ratio of fungal to bacterial biomass is often supposed under arable cultivation due to the disruption of fungal hyphae by soil tillage (Brussaard et al. 1996). Gosling et al. (2006) showed inhibition of AM colonisation of roots and spore numbers in tilled fields. Allison et al. (2005) found that cessation of tillage-based agriculture did initially lead to an increase in the abundance of fungi, particularly arbuscular mycorrhizal (AM) fungi, relative to bacteria; however this can be related to the extent and duration of active root biomass in the different systems as much as soil disturbance due to tillage.

For large animals, exposure at the soil surface and consequent predation is a major cause of population reduction following tillage as recently summarised by Roger-Estrade et al. (2010). However, for most species the effects on populations are as a result of immediate but indirect effects arising as a result of the modification of soil habitats, particularly the continuity of water filled pores and water films (Winter *et al.* 1990). Consequently smaller impacts of changes in tillage practice are often seen on very sandy soils (Spedding *et al.* 2004) as these soils may have communities of soil biota adapted to environments with low connectivity. Van Eekeren et al. (2008) showed that for many species ley-arable systems (3 years arable, 3 years ley) allowed recovery of species during the ley phase, though there remained significant differences in population composition between ley-arable rotations and permanent grassland – as a result of the interaction between tillage and organic matter levels. Anecic earthworms were reduced by tillage much more than endogeic earthworm species (van Eekeren et al. 2008).

Table A2 Summary of tillage impacts on below-ground organisms (updated from Stockdale *et al.* 2006)

Species/group	Average impact of tillage or increased tillage intensity	Key references
Bacteria and archaea	Mild inhibition	Wardle 1995
Rhizobia	No evidence found	
Nitrifiers	Little evidence, stimulation of group 3 *Nitrosospira* (but not group 4) by cultivation	Mendum and Hirsch 2002
Fungi	Mild inhibition	Wardle 1995; Allison et al. 2005
AM fungi	Inhibition of AM colonisation of roots and spore numbers	Gosling *et al.* 2006
Protozoa	Little evidence, minor impact	Foissner 1997
Nematodes	Little effect; mild stimulation of bacterial feeders, mild inhibition of fungal feeders and omnivores	Wardle 1995
Mites	Moderate to mild inhibition, some studies show stimulation	Wardle 1995
Collembola	Moderate to mild inhibition, some studies show stimulation	Wardle 1995
Enchytraeids	Little effect, as often stimulated as inhibited.	Wardle 1995
Earthworms	Moderate to extreme inhibition	Postma-Blaauw *et al.* 2010; Roger-Estrade et al. (2010)
Insects	Moderate to extreme inhibition	Wardle 1995

In addition to the impacts of tillage *per se* comparisons of arable systems cultivated by conventional and no-till methods show differences in plant biomass, which may have indirect effects on below-ground ecology. Adl et al. (2006) showed an increase in soil OM and profile stratification with the duration of no-till management across a chronosequence of sites. During the first 8 years of no-tillage there was some increase in the abundance of soil organisms, with larger organisms responding more quickly to the no-till management, but only the two older fields (8-26 years) had biomass and species richness of soil biota that approached that of undisturbed sites. These changes are likely to be a result of interactions between reduced disturbance, changes in rooting patterns and soil OM. No-till systems consistently show higher root biomass near to the soil surface (Anderson 1987) as well as deep penetration of roots in earthworm burrows (Cheng *et al.*, 1990). It might therefore be expected that spatial patterns of root exudation, if not also total amounts, might vary between conventional and no-till systems. Significant long-term increases in the quantity of organic carbon or microbial biomass have also been shown in a variety of reduced tillage systems e.g. Balesdent et al. 2000 and Vian et al. 2009. Placement of crop residues also differs between the systems and no-till systems often show an increased stratification of OM content in what was previously the plough layer (Kay and vandenBygaart 2002). These indirect effects of tillage regimes on plant root patterns may have as significant effect as tillage *per se* on below-ground ecology, not least in the promotion and persistence of greater small scale heterogeneity in no-till systems. Simmons and Coleman (2008) showed no clear chronosequence in the development of soil microbial communities with increased biomass and diversity following cessation of tillage; they hypothesised that any apparent "conversion period" for soils in conservation tillage (no till) system are as a result of the time required to build organic matter in situations where soils had previously received very low inputs during conventional cultivation.

Additional tillage operations are often used, if weed management through herbicides is ineffective or restricted (such as where resistant weeds are present or in organic farming). Earthworms seem to benefit more from weedy conditions more than other species groups (Tomlin and Fox, 2003). Manipulation of ground cover and removal of weed species may have particular negative impacts for rhizobia and AM fungi, where weed species may act as hosts; weeds are particularly important as bridges if the main crop is not a host species (Kurle and Pfleger 1996).

2.3 Plant / crop species

Most below-ground organisms are heterotrophic and hence dependent on the decomposition of sources of C in soil rather than photosynthesis or autotrophism for energy. In managed agroecosystems, a key human intervention driving the biomass, activity and diversity of soil biota is therefore the selection of crop plants determining the species richness, genetic variability and organisation in space and time of crops, if not of weeds. The extensive review of Wardle (2002) showed that above–ground net primary production is not strongly or simply related to the biomass of bacteria and fungi (as primary decomposers) below-ground in all systems. Plant productivity is coupled to below-ground ecology through amount and quality of litter or residues returned (considered in more detail in Section 2.5), root growth, exudation and a range of rhizodeposition mechanisms in the soil (Dennis *et al.* 2010). The presence of particular host species e.g. legumes provides opportunities for direct plant-microbe associations. Plants also compete with the soil biota for available nutrients, water and other resources below-ground and it is not clearly established to what extent this competition is an important regulatory mechanism in below-ground ecology (Wardle 2002). In addition the biomass of bacteria and fungi measured may be limited by predation. These mechanisms are difficult to separate in the field.

The cultivation of different crops in arable systems is usually associated with a range of other changes in management practices, as well as differences in relation to duration of crop cover and growing season, amount and quality of OM inputs. Crop species also differ in the mass of roots produced and in the depth and pattern of rooting (Gregory 2006) as well as the amount and quality of root exudates (Marschner *et al.* 2001). For example, Van Eekeren et al. (2009) showed that the root system of a sole crop of grass was up to three times denser than the root system of white clover after two growing seasons. These differences between crops may have short-term and/or long-term effects on below-ground ecology. The biomass and diversity of soil biota been shown to be different under different plant species both those typical of grasslands (Groffman *et al.* 1996; Grayston *et al.* 1998; Bardgett *et al.* 1999; Porazinska *et al.* 2003) and cropping systems (Grayston *et al.* 1998; Porazinska *et al.* 2003).

Osler *et al.* (2000) showed that crop phenology e.g. leaf fall in the senescent crop phase and/or canopy structure with consequent exposure of soil, has a major effect in driving the seasonal variation of soil mite communities under crops (wheat, lupin, oilseed rape) grown in rotation. Postma-Blaauw *et al.* (2010) measured significant differences between potato, maize and barley crops; these crops have very different tillage systems as well as differences in organic matter inputs. Differences between the composition and structure of populations of soil biota in long-term pasture and arable crops are well known but relate to tillage (described above) as well as the plant factors outlined here (van Eekeren et al 2008).

Griffiths *et al.* (1992) showed some indication of differences between grass species in their effect on below-ground species with *Poa annua* and *Poa pratensis* supporting larger bacterial numbers in the rhizosphere than *Lolium perenne* or *Festuca arundinacea*. Bardgett *et al.* (1999b) also found that those grass species which co-dominate the total plant biomass of intermediate fertility (*Holcus lanatus*) and semi-improved grasslands (*Agrostis capillaris* and *Festuca rubra*) generally had a beneficial effect on soil microbial biomass. In contrast, the dominant plant species of improved grasslands, *Lolium perenne*, had zero or a negative effect on soil microbial biomass. However, under field conditions, van Eekeren *et al.* (2010) showed no differences in impacts of different grass species (*Lolium perenne, Festuca arundinacea*, *Dactylis glomerata*) sown in pastures over two growing seasons on soil biota. Griffiths *et al.* (1992) also found differences between grass species in their effect on protozoa, nematodes and enchytraeids.

While rhizosphere communities of bacteria are largely plant species specific, the development of the associated soil community is controlled by a complex interaction of soil and plant factors (Marschner *et al.* 2001). In practice therefore differences between the impacts of plant species on soil biota are a mixture of direct and indirect effects; observations under pot culture or with monocultures may not be reproduced in the field and/or with plant species mixtures. Van Eekeren *et al.* (2009) showed that under field conditions pure white clover stands were associated with lower soil microbial biomass, a higher proportion of bacterivorous nematode dauerlarvae and fewer herbivorous nematodes than a grass only sward; this was linked to the difference in root biomass and distribution. Marilley and Aragno (1999) also showed that the bacterial community structure associated with grass and clover roots within a sward varied markedly between these plant species using molecular techniques. However, in mixed grass-clover swards (20-30% clover in DM), active N fixation can support additional yield and root growth (similar to moderately fertilized grass) leading to positive impacts on soil biota and increases in earthworm biomass which can be explained as a result of the interaction between the quantity and C/N ratio of the root and plant litter inputs (van Eekeren *et al.* 2009).

The strong specificity of many microbe-plant relationships in the root, rhizoplane and rhizosphere suggests that an increase in plant diversity, whether in space (intercropping) or time(crop rotation) , is likely to lead to changes in soil biota species dominance below-ground and perhaps also an increase in diversity (Lynch *et al.* 2004). Work on restoration of upland hay meadows in the UK (Smith *et al.* 2008) found that manipulation of plant species diversity through targeted seed /transplants followed by careful management of grazing/cutting and fertility inputs over 14 years was an important step in converting bacterial-dominated soil microbial communities typical of intensively managed grassland systems to fungal-dominated communities, more typical of traditional systems.

The presence of particular host plants is well known to be critical for the survival of certain root-associated species e.g. for rhizobia, AM fungi and pathogenic species. Knowledge of the survival strategy of the particular organism in the absence of a host plant is important for rotation planning either to maintain populations (Rhizobia and AM fungi) or to break the pathogen/host cycle. The presence of fallow periods or non-host crops for AM fungi (e.g. brassicaeous species) in a rotation was shown to reduce propagule numbers, and AM fungal colonisation of subsequent crops significantly (Gosling *et al.* 2006). Species and even cultivars may show different root exudates or leachates that either stimulate (susceptible crops and varieties) or inhibit (resistant crops and varieties) the germination of specific pathogenic organisms (Bateman and Kwasna 1999; Tsror 2010). Several wheat cultivars developed prior to 1950 have been shown to benefit more strongly from mycorrhizal mutualisms than modern wheat cultivars (Hetrick *et al.* 1992, 1993). Zhu *et al.* (2001) also found that mycorrhizal responsiveness of modern wheat cultivars, measured in terms of shoot P, was generally lower than that of older cultivars. Such an observation has also been reported for plant associations with beneficial microorganisms other than mycorrhizal fungi. For example, root endophytes such as *Azoarcus* spp. or *Neotyphodium* and *Acremonium* preferentially colonized wild species and older varieties over modern cultivars of rice (Engelhard *et al.* 2000) and wheat (Marshall *et al.* 1999), respectively. These differences between cultivars may result from the approach to cultivar selection in crop breeding which has typically been performed in standardised, high fertility soil conditions with a primary focus on yield. Under such conditions, benefits incurred through interactions between plants and beneficial soil microorganisms may have been made obsolete by the excess provision of nutrients in readily plant available forms and hence disregarded during selection (Wissuwa et al. 2009).

2.4 Crop rotation / impacts of previous crops

In most cropping systems mono-cropping is the exception and the majority of cropping systems include a distinct break crop to interrupt host/pathogen interactions. Any change in crop rotation is likely to also result in a number of other management changes, in addition to changes in crop order. In a long-term experiment, Houot and Chaussod (1995) showed that the effects on soil properties and below-ground ecology of changes to management practices in crop rotations can take a long time to reach equilibrium; hence studies of previous crop effects in the less-controlled “real world” are complicated by these temporal dynamics. There are few studies of the impact of a previous crop or crops on below-ground ecology. However, some indications that these effects are significant in the field have been shown e.g. certain cultivars of red clover have been found to foster the development of endophytic bacteria that promote the growth of subsequent potato crops (Sturz and Christie, 1998). However, Postma-Blaauw *et al.* (2010) found little effect of preceding crop on nematode abundances, which responded rapidly to the current crop as it established.

Perhaps not surprisingly rotation effects have been most studied in relation to the persistence and effectiveness of mycorrhizal fungi. Spore formation is a crucial life history strategy for AM fungi as the asexual chlamydospores, recently called glomerospores (Goto and Maia, 2006), are transitorily dormant, persistent propagules that remain infectious in the absence of host plants and can survive under unfavourable conditions (Klironomos and Hart, 2002). Thus interactions between crop rotation and the sporulation patterns of AM fungi are important in determining the persistence of the mycorrhizal fungi. Oehl *et al.* (2009) found clear successional and seasonal dynamics of spore formation, implying different life strategies of different AM fungi species. Oehl et al. (2009) found higher species richness of AM fungi in microcosms of grasslands and the arable lands subjected to crop rotation than in the microcosms from maize monocropping systems with AM fungi, belonging to specific ecological groups, lost under high-input maize monocropping. Johnson *et al.* (1992) also found that mono-cropping seems to select for AM fungal species that offer limited benefits to the main crop plant. Increasing the diversity of hosts by crop rotation generally increases the diversity of AM fungal species (Gosling *et al.* 2006), but it is also clear that non-mycorrhizal hosts within the rotation will have negative impacts. Oehl *et al.* (2003) showed that increased cropping diversity coupled with reducing tillage within a cropping sequence (in a study using a gradient of sites from intensive mono-cropped maize to species rich grassland) led to an increase in the species richness of AM fungi.

Diversification of rotations has been recently promoted through the inclusion of cover crops which in the UK are planted in late summer or autumn to provide soil cover during the winter. The primary aim of cover crops is to reduce soil erosion resulting from bare soil overwinter. A separate but related use of overwinter crops is as catch crops which are deliberately selected for their ability to rapidly take up nitrogen from soil and hence reduce overwinter leaching of N. Green manuring is a related but distinct practice which involves the soil incorporation of any field or forage crop while green or soon after flowering, for the purpose of soil improvement; green manures are often legumes. Relatively few cover crop and green manure species are not also common crop species (in part due to seed costs); impacts of use of cover crops often relate to increased inputs of OM to the soil during cover crop growth and in residues. For example, inclusion of cover crops with no other changes in the crop rotation, led to an increased size of the microbial biomass in a vegetable cropping system (Schutter and Dick 2002).

It has recently been proposed that brassicaeous species (including oilseed rape) can have a biofumigation effect on soilborne pathogens as a result of allelochemicals released into the rhizosphere during crop growth (Rumberger and Marschner 2003) and/or when the crop residues are decomposed in soil (Bending and Lincoln 1999). This approach, if verified, harnesses interactions between above ground crop management and the soil biota to modify the epidemiological attributes of the pathogens and reduce the need for soil sterilisation e.g. in controlled cropping situations. A recent review (Motisi *et al.* 2010) highlights that site and soil characteristics and biofumigation techniques e.g. whether the residues are incorporated, growing season, time between residue incorporation and sowing of the test crop will all affect biofumigation effectiveness. However, in practice Smith *et al.* (2004) could show no evidence of benefits to the growth of following wheat crops of biofumigation using *Brassica* crops or evidence of any significant changes in species richness in the soil microbial community.

The use of monocultures, or simplified rotations, reduces both above and below ground biodiversity (Culman *et al.* 2010). The design of both the crop rotation and the farm landscape are critical in contributing to the conservation and enhancement of soil biota (Jackson *et al.* 2007). For many insect species, a range of habitat types is required during the species' lifecycle – loss of any habitat component could critically affect species survival even where the remainder of the habitat is in pristine condition. For soil biota (including crop pests), field margin habitats may provide an important buffer and maintain a source of organisms able to re-invade cropped land following disturbance (Blackshaw and Vernon 2006; Woodcock *et al.* 2007).

2.5 Crop residue management

Return of crop residues (in contrast to baling and removal) has been shown in some studies to make a larger contribution to the increase in size of the soil microbial biomass than decreasing intensity of tillage (Spedding *et al.* 2004). The relative magnitude of these effects is strongly dependent on the soil type (Spedding *et al.* 2004). Reductions in the microbial population density and diversity were observed following stubble burning; this was linked to reductions in amount and availability of OM (Rasmussen and Rohde 1988). Increases in soil microbial biomass are commonly measured where residues are incorporated rather than removed or burnt (Powlson *et al.* 1987). However, increased OM input from plants has been linked to stimulation in the bacterial feeding microfauna (nematodes and protozoa) without a concomitant increase in the size of the bacterial population; the stimulation of the bacteria population is kept in check by predation (Wardle 1995; an example of a tri-trophic effect within the soil food web). Christensen *et al.* (1992) showed a rapid but ephemeral (up to 20 days) increase in protozoa and bacterial feeding nematodes (to populations 80 and 30 times greater than the initial population sizes respectively) in the vicinity of a freshly-killed barley root. These increases did not stimulate larger predators, perhaps because of their short duration.

The amount and quality of crop residue returns are well known to affect mineralisation processes in soil (Swift *et al.* 1979); However, there has been much less study of the impact of residue returns on microbial community structure. Bending *et al.* (2002) showed smaller differences than they had expected in microbial community functional diversity (measured by enzyme profiles and Biolog) as a result of the addition of a range of crop residues. Residues with high lignin contents seemed to have a greater short-term influence on microbial community, whereas low lignin residues with a range of other characteristics showed increased population sizes but little difference in functional diversity (Bending *et al.* 2002). Bailey and Lazarovits (2003) assembled substantial evidence from the literature to show that rapidly decaying plant residues (with low C:N ratios) reduce the numbers of pathogenic species while at the same time increasing the total bacterial and fungal biomass. They attributed the effect to the impact of high NH_3/NH_4^+ concentrations produced during mineralisation on pathogen populations rather than microbial competition. It has also been suggested that the microbial biomass is adapted to "specialise" in decomposition of the dominant litter type (Cookson *et al.* 1998). However, more recent studies do not provide strong evidence to support this hypothesis (Ayres *et al.* 2006).

2.6 Mineral fertilisers

Mineral fertilisers are a major input into UK agriculture to meet plant nutrient demand and maintain a balanced nutrient budget. There is a range of fertilisers in common use – ammonium nitrate (as solid and liquid, with additional urea), diammonium phosphate, triple superphosphate, muriate of potash (dominantly potassium chloride), also as compound fertilisers.

It is often considered that there is a direct effect of high levels of soluble P in soil on colonisation of roots and propagule density of AM fungi. However, a small number of studies have reported contradictory results. Harrier and Watson (2003) suggest that the effects of soluble P fertilisers on AM fungi-crop relationships are affected by the P status of both the crop and soil under study. The use of rock phosphates (which are a very slow release source of P) has no effect on AM fungi (Ryan *et al.* 1994). Different isolates of AM fungi differ in their sensitivity to soil P and consequently at low and moderate levels of soil P impacts of P fertiliser on colonisation and the effectiveness of the AM-root association may vary depending on the isolate involved (Harrier and Watson 2003). The literature also provides mixed evidence of the effects of N fertiliser on AM-root associations (Gosling *et al.* 2006). A review by Johnson (2010) highlights that the differences in AM symbiotic function in the field can be linked to the relative availability of carbon, nitrogen and phosphorus to the AM fungi and that allocation to plant and fungal structures depend on the integrated availabilities of these resources; hence relationships with nutrient concentrations in soil are multi-factorial (Hoeksema *et al.* 2010). It was established early in the study of N fixation that large soil nitrate concentrations reduced effectiveness of nodulation in legumes (Nobbe and Richter 1902) but soils receiving high applications of N fertiliser can still support large populations of rhizobia.

Application of some N and S fertilisers (particularly ammonium sulphate) is known to reduce soil pH. Sarathchandra *et al.* (2001) measured changes in nematode species composition resulting from pH changes after fertilisation. Earthworm populations are also reduced with increasing acidity (Edwards 1998). Where long-term acidification from fertilisation of grassland is not remedied development of a mor humus form will result due to the reduction in comminution and decomposition of plant litter (e.g. van Bergen *et al.* 1998). P fertilisers often contain trace heavy metal contaminants (Cd, Hg, Pb; McLaughlin *et al.* 2000), hence, where P fertilisers have been used regularly long-term chronic toxicity might arise. However, this is more often a problem with contaminated organic amendments (Giller *et al.* 1998).

Within fertiliser studies it is almost impossible to separate any direct effects on below-ground ecology from feedbacks as a result of plant nutrition (Dick 1992). Short term impacts may be mediated via changes in the amount and composition of root exudates e.g. Marschner *et al.* (2004). Paterson and Sim (1999) found that N limited plants in grassland had a higher proportion of plant-assimilated C directed to root exudation; this may lead to a larger more active soil microbial community in N-limited grassland (Yeates *et al.* 1997).

Long-term fertiliser treatments leading to consistent differences in yields (and residue returns) are usually associated with increases in SOM and microbial biomass (Marschner *et al.* 2004, Murphy *et al.* 2003) particularly where crop residues are returned. As outlined earlier van Eekeren et al. (2009) showed that N inputs via fixation had the same effect on soil biota as N fertilizer for grass or mixed grass-clover swards as a result of impacts of improved nutrient supply on the quantity and C/N ratio of the root and plant litter inputs. Nematodes and protozoa tend to show positive responses to fertiliser application, but little impact of application of fertiliser on soil microbial biomass, possibly a further example of a tri-trophic effect within the soil food web. Consequently it is not surprising that a range of effects on larger predatory soil animals have been shown in grasslands as a result of fertiliser application (Bardgett and Cook 1998).

2.7 Organic amendments

Organic amendments used in agriculture include a diverse range of materials produced on and off-farm, including microbial, plant, and animal wastes, and by-products of the food processing industry. The most common wastes used on agricultural land are those resulting from livestock housing on farm. Increasingly farmers are looking beyond the farm gate for sources of organic amendment and there is increasing production of certified green waste composts (PAS 100) and their use on agricultural land. Organic amendments have been used on agricultural land partly to facilitate their disposal, but also to help meet plant nutrient demand and/or as soil conditioners (Quilty and Cattle, 2011).

2.7.1 On-farm management of organic manures

Amendment of soil with raw and/or composted organic amendments generally leads to an increase in the soil microbial biomass population e.g. Marschner *et al.* (2003). The duration of this effect depends on the amount and quality of OM added; sustained changes are most likely where organic amendment is regular. On farm in the UK animal manures from housed livestock are collected and handled both as solids (farmyard manure) and/or liquids (slurry); housing design largely determines the forms of manure produced on each farm. Application of livestock manures then may be as raw (fresh) materials or following storage and sometimes treatment. Currently the main approaches used on farm for manure treatment are i) composting systems or related technologies producing a useful solid product; ii) biological systems for liquids that effectively breakdown some of the organic load; and iii) separation systems concentrating solids which can then be composted and/or concentrating of available nutrients in a clarified liquid fraction (Martinez et al. 2009).

Populations of protozoa, bacterivorous and fungivorous nematodes tend to show short-term increase after organic amendments, particularly where the amendments have low C:N ratio (e.g. Bongers and Ferris, 1999; Griffiths *et al.* 1994, Porazinska *et al.*, 1999) and hence are rapidly decomposed. Populations of protozoa tend to increase more quickly and peak much earlier than nematode populations (Opperman *et al.* 1989). Increased populations of bacterial feeding nematodes can be linked directly to increased populations of bacteria associated with the input of organic amendments (Griffiths *et al.* 1998; Bulluck and Ristaino, 2002). In contrast the use of organic amendments has been shown in some studies to reduce the numbers of plant feeding nematode species (Griffiths *et al.* 1994). As well as the immediate short-term effects, long-term application of organic amendments have also been shown to increase seasonal average nematode populations as a result of the increase in soil OM and soil microbial biomass (Corbett *et al.* 1969). The use of organic amendments including composts and FYM seems to have no negative and often a positive effect on the biomass and effectiveness of AM fungi in forming plant-fungal associations (Harrier and Watson 2003).

Not all organic amendments show the same impacts, especially on a short-term basis and this is most strongly related to the proportion of C in the added material that is readily available for microbial utilisation and hence the rates of decomposition (Griffiths *et al.* 1998; Marschner *et al.* 2003). Rapidly decomposing manures (with low C:N ratios) reduce the numbers of pathogenic species while at the same time increasing the total bacterial and fungal biomass (Bulluck *et al.* 2002). Bailey and Lazarovits (2003) attributed the effect to the impact of high NH_3/NH_4^+ concentrations produced during mineralisation on pathogen populations rather than microbial competition. They also showed that application of organic amendments, such as slurries, that are rich in available N on application may reduce soil-borne diseases. A range of other allelopathic and competition effects may also play a role particularly in soils which receive regular organic amendments (Bailey and Lazarovits, 2003).

A range of application methods are used, especially for liquid manures, which largely seek to reduce NH_3 volatilisation losses. In a comparison of surface applied (high NH_3 loss risk) and slit injection of slurry on 12 farms in the Netherlands, slit injection negatively affected epigeic earthworms, whereas its effect on anecic and endogeic earthworms was absent or even positive (De Goede *et al.* 2003). Surface applications of dairy manure (Peacock *et al.* 2001) increased the number and proportion of bacteria, which are able to respond rapidly to added soluble organic C. The largest effects were seen in the surface (0-5 cm) but changes in the microbial population were also seen at lower depths, probably due to increased leaching of soluble C and other nutrients (Peacock *et al.* 2001).

Following more than 100 years of manure application Sun *et al.* (2004) measured bacterial soil diversity using molecular methods and showed increased soil species richness with increased evenness (reduction in the importance of the most dominant species) in comparison with plots receiving no additions or long-term mineral fertiliser. In a long-term trial in Sweden, Sessitch *et al.* (2001) also observed increased species richness of bacteria in soils receiving green manures and well rotted farmyard manures compared with plots receiving mineral fertiliser, though microbial community structure was more significantly affected by soil texture than any of the amendments used. Jangid *et al.* (2008) showed that plots where poultry manure applied for at least 10 years had increased total microbial biomass and found that the community structure was significant different with greater species richness and evenness compared with mineral fertiliser; they linked the differences to changes in soil physico-chemical parameters following manure amendment, especially increases in pH and soil OM. However, no differences were found between fertiliser, manure and control plots of the long-term Broadbalk continuous wheat experiment, where both phylogenetic and functional gene analyses showed similar bacterial communities in all the treatments with all samples containing a range of eubacterial taxa similar to those that are characteristic of soil bacteria reported elsewhere which seem to be relatively non-responsive to long-term management of balanced fertilizer inputs (Ogilvie *et al.* 2008).

In a long-term comparison of farming systems under the same crop rotation in Switzerland (DOK trial), the abundance and activity of soil biota were shown to be more sensitive than the total soil organic carbon pool to differences in the quantity and quality of applied animal manures; a critical difference between the farming systems was in the handling of manures so that manure was applied either fresh, after 6 months in a field stack or following managed composting (Flieβbach *et al.* 2007). Zaller and Köpke (2004) showed significant increases in the soil microbial biomass and activity and in earthworm casting activity (120% of untreated plots) after 9 years application of composted manure in an arable rotation; they also showed some smaller, but significant, differences in the temporal pattern of manure decomposition (over the first growing season after application) between manures depending on whether and how treatments required by biodynamic farming practices had been used during the composting process. There is some evidence that these preparations affect the microbial community, which develops in the manure during the composting process (Carpenter-Boggs *et al.* 2000).

Where farmers are composting manures on-site, they may also prepare compost extracts or compost teas as plant and soil amendments. The preparation of compost tea usually involves steeping compost in water for a defined period under aerobic conditions, often adding other substances such as seaweed extracts, fish hydrolysates, or molasses to the mixture. The resulting liquid is then applied as a foliar or a soil spray. There is very limited data on the on-farm production and use of compost tea when applied as a soil treatment in the literature; Hargreaves et al. (2009) and Knewtson et al. (2009) found little effect of compost tea on plant growth or soil microbial biomass and its activity other that might be predicted from its nutrient content.

2.7.2 Brought-in organic amendments

Because of the range of off-farm organic amendments available relatively little work has been done on their impacts on soil biota. A wide range of organic amendments are now available commercially to farmers; see for example the list provided by Quilty and Cattle (2011). Most of these materials are produced from waste materials; however, careful life cycle analysis is needed to evaluate the broad-scale environmental impacts, especially where materials might be produced specifically for land application (e.g. seaweed, biochar). Much of the information about agriculturally beneficial effects of such amendments is consequently the result of single trials or short-term multiple site experiments. However, the same general principles applying to both quantity and quality of OM inputs discussed above in relation to crop residues and on-farm manures will also apply.

Ge *et al.* (2010) showed that the effects of off-farm organic wastes on soil bacterial communities varied with the types of organic wastes, and depended on the rate of application; the C:N ratio of one organic waste applied (> 400, grease trap waste) was a major driver for a significant observed change in the soil bacterial community measured by molecular methods. Well matured composts show OM quality (C:N) ratios very similar to that of humified soil OM; hence it is not expected that matured composts will have any detectable impact on the diversity of the soil biota at typical rates of application (10-30 t ha^{-1}). Crecchio *et al.* (2004) demonstrated clearly using a range of molecular techniques that while application of municipal waste compost (for 6 years) slightly increased the biomass and activity of the bacterial community over this time period, the species richness determined by molecular methods was not affected; Tiquia *et al.* (2002) showed that the use of composted green waste as mulch (over 3 years) also significantly increased bacterial population compared to plots with wood chip as mulch or unmulched plots.

Long-term amendment of plots with sewage sludge (metal contaminated) or peat also led to bacterial communities that were very distinct from those where on-farm sources of animal or green manures had been applied (Sessitch *et al.* 2001). Differences between soil microbial populations have also been seen even at relatively low rates of sludge application (Banerjee *et al.* 1997). Heavy metal contamination in sewage sludge has been shown to reduce N fixation in clover due to negative impacts on biomass and diversity of rhizobia populations (Giller *et al.* 1998; Hirsch *et al.* 1993). Abaye *et al.* (2005) showed significant differences in the structure of the bacterial community in soils which had been contaminated with metals as a result of regular sewage sludge additions even 40 years after the application of sludge had ceased. Macdonald *et al.* (2011) demonstrated dose-related effects of metals in applied sewage sludges (11 years after application ceased) on bacterial, archaeal and fungal communities implying a progressive change in community structure in response to increasing metal concentrations; however, the metal effects were comparatively weak compared to the effect of site. The functional consequences of the changes in the soil microbial community effects are yet to be determined for this experiment. Applications of sewage sludge can also increase soil concentrations of persistent organic pollutants which can show negative effects on below-ground ecology (Wilson *et al.*, 1997; Hill 2005); there is generally insufficient data currently available to carry out appropriate risk assessments for this practice. In general long-term chronic toxicity of heavy metals and persistent organic pollutants is more common than immediate, acute toxicity and more often associated with contaminated organic amendments from urban or industrial sources (Giller *et al.* 1998).

Amendment of soils with seaweed (often kelp) has been a common practice in coastal areas. Benefits are believed to accrue from both nutrient mineralisation and structural stabilisation as a result of the release of algal polysaccharides. Haslam and Hopkins (1996) showed that impacts on soil structure were the important driving mechanisms for impacts on soil biota and plant productivity; however, more recently Thorsen *et al*. (2010) showed that on calcareous shell sands kelp addition has relatively little effect on soil microbial biomass and its activity or soil structure formation and stabilisation. Khan et al. (2009) have recently reviewed the potential for seaweed and seaweed extracts as biostimulants and concluded that currently the mechanism(s) governing the response of plants to seaweed extract are largely unknown.

Recently there has been significant interest in the application and use of biochar amendments. The molecular structure of biochars shows a high degree of stability to chemical degradation or microbial decomposition and they have a highly porous structure and large surface area. It has been suggested that this structure can provide refugia for beneficial soil micro-organisms; however, there is currently little evidence of the impacts of biochar use in practice on soil physical, chemical or biological properties under temperate conditions (Atkinson et al. 2010). A recent review of biochar impacts on the soil biota (Lehmann et al. 2011) suggested that research was confounded by the wide range of physico-chemical properties of biochar materials. Most studies showed increases in microbial biomass following biochar application, and this seems largely attributable to biochar presenting physical niches for microorganisms, and greater co-location of these organisms with sorbed nutrients. The sorption of chemicals that might inhibit biological activity in the wider soil was also a possible effect enhancing biological activity, but organic molecules released from biochar were sometimes responsible for suppression of biological activity and functions. Spokas et al (2009) found that biochar addition reduced basal respiration, N_2O emissions, and increased sorption of pesticides, but also suppressed methane oxidation, resulting in higher methane emissions. This suggests a suppression of a range of soil biological functions, and indicates that biochar may be more suited as a carbon storage strategy than one to enhance soil biological activity.

3.0 Specific targeted (point) interventions

3.1 Pesticides

Pesticides are a diverse group of chemicals used to control insects and other organisms harmful to cultivated plants and animals. Studies of pesticide impacts usually consider applications of single components rather than the full diverse programme of an in-field pesticide regime; the majority of studies are carried out under controlled rather than field conditions. The timing of an application in relation to the life cycle of fauna is also critical in determining the impact on target and non-target species (Frampton and Çilgi, 1996). Little is known about the impact of the formulation ingredients of pesticides e.g. adjuvants (dos Satos *et al.* 2005). It is therefore difficult to assess the likely impact of field use of pesticides on soil biota (Gosling *et al.* 2006).

Hart and Brookes (1996) showed little evidence of long-term harmful effects of the use of typical range of agricultural pesticides, singly or in combination, on the soil microbial biomass or its activity (Hart and Brookes 1996). Foissner (1997) reviewed a range of data mostly collected in laboratory microcosms on the impact of some pesticides on soil protozoa; in many cases fluctuations in other variables such as food resources and /or temperature had as large an effect as pesticide use. Overall it was concluded that insecticides are usually more toxic than herbicides and disturb soil protozoa critically, i.e. populations often do not fully recover within 60 days; fungicides have rather varied effects but most of them very likely do not influence soil protozoa critically. When applied at recommended rates to plants, few fungicides have been seen to have significant effects on mycorrhizal colonisation (Gosling *et al.* 2006). Where effects are seen these are often short-term e.g. Smith *et al.* (2000).

Long-term negative effects are seen where copper-based fungicides have been used for a number of years due to the accumulation in the soil of Cu to levels which are toxic. Most effects in the field are seen in orchards and vineyards where negative effects on earthworms have been recorded (Filser *et al.* 1995; Van Zweiten *et al.* 2004; Eijsackers *et al.* 2005; Loureiro *et al.* 2005). Use of Cu-based fungicides was also shown to lead to increased stress responses in microbial populations (Merrington *et al.*, 2002). Chu et al. (2010) demonstrated the tolerance of fungal biomass to Cu (relative to other microbiota) given adequate energy resources – in this instance provided by green manure incorporation; however, there was a change in fungal community structure with some species replacement in heavily contaminated soil. Cu is readily fixed by the soil matrix and long-term effects are likely to persist even where Cu applications cease as for the use of metal contaminated sewage sludge discussed above.

At typical rates of application, there is no evidence for any detectable direct effects of herbicides on microbial biomass size or activity, protozoa, collembolae, nematodes and earthworms (Wardle 1995; Hart and Brookes 1996). Lins *et al.* (2007) found that treatments receiving atrazine and 2,4-D showed significant reduction of Collembola populations; the magnitude of the effect dependent on the time of application and hence the environmental conditions. Greenslade *et al.* (2010) detected a significant effect of the herbicides, bromoxynil ($C_7H_3Br_2NO$) and hoegrass (diclofop-methyl), reducing the activity of two surface-dwelling Collembola species (of fourteen species observed) but no effect was observed on surface-active ants. Powell et al. (2009) studied the effects of transgenic, glyphosate-tolerant (GT) crops and their management, particularly the increased use of glyphosate herbicide in such systems, on the abundances of detritivorous soil biota and crop litter decomposition. They found that absolute abundance of few of the measured biotic groups were affected by the herbicide treatments, and, where significant effects were observed, the responses were not consistent. Herbicides have a range of direct effects on plant cover (restricting weed emergence and/or growth and reducing competition to crop growth) which are likely to result in a range of indirect effects on below-ground ecology. House et al. (1987) found that herbicides applied twice (preemergence and mid-bloom) at recommended field rates including combinations of paraquat, glyphosate, alachlor, linuron, fluazifopbutyl, aciflurofen, and bentazon had no impact on microarthropod numbers, suggesting that abiotic factors such as soil temperature and moisture were probably more significant than herbicide effects in regulating soil microarthropod number and activity. Enhanced macroarthropod numbers in non-herbicide treatments at the end of the season were linked to moist soil and litter, low soil temperature, floral diversity, and high weed-seed availability rather than direct herbicide effects.

House et al. (1987) found that decomposition of non-glyphosate treated surface crop residues was more rapid than glyphosate treated, which may result from changes in residue quality and/or inhibition of the decomposer community. Blackshaw and Lindwall (1995) showed no effect of herbicide applications (glyphosate, paraquat, and 2,4-D) on residue decomposition. However, Powell et al. (2009) found that overall the use of glyphosate reduced rates of soybean- and maize-litter decomposition, but responses were inconsistent and strongly interacted with environmental conditions.

3.2 Soil Fumigation

Fumigation of soils to control soilborne pathogens, nematodes and weeds is a tool associated with the intensive cultivation of some vegetable, fruit and nursery crops. The most common fumigant in recent times has been methyl bromide often applied in combination with chloropicin. However, the use of methyl bromide is being phased out, by international treaty as a result of its greenhouse gas potential, and alternative fumigants have been developed. Differences are often observed in the short-term response of soil organisms to fumigation since soil temperature and moisture content affect the efficacy of fumigation. However, in general, all fumigants show an immediate reduction (up to 1 week) of soil microbial activity (respiration and enzyme activities), but after 30 weeks there is little difference between fumigated and unfumigated soils (e.g. Klose and Ajwa 2004). It has been hypothesised that repeated fumigation may lead to long term adaptation of the microbial population with loss of sensitive species and selection for resistant species. Miller *et al.* (1997) showed an increase in the population of microbes able to use fumigants as a source of C and/or energy. Initial work suggests that the alternative fumigants developed to replace methyl bromide have smaller effects (Klose and Ajwa 2004). However, it should not really be a surprise that a blunt management technique such as fumigation should have significant effects on below-ground ecology. Soils which have been repeatedly sterilised by fumigation such as in conventional strawberry production show very significant changes in soil microbial communities (Reeve *et al.* 2010) compared to paired sites under organic production where fumigation is not permitted. While the use of composts can mitigate the impacts of fumigation to some extent (Dungan *et al.* 2003), it seems that there is a long-term cumulative impact on the population structure of the soil biota of repeated fumigation (Reeve *et al.* 2010); this may be therefore require considerable intervention to restore.

3.3 Soil Inoculants

Where a microbial species/ genera has been identified as having a positive impact on plant growth there are two approaches available to the land manager i) to enable and develop the indigenous populations through a range of systems-oriented practices as outlined in Section 2 of the main report or ii) to isolate and apply the target micro-organisms as inoculants to promote their biocontrol or plant-growth promoting functions at the target site (Berg, 2009) Microbial inoculants are currently used in relatively limited circumstances in the UK.

It has been known for over 100 years that where a legume species is to be grown for the first time it is beneficial to deliberately introduce the nodulating micro-organisms (Stockdale and Brookes, 2006). Rhizobial inocula are now produced for sale routinely and usually contain around 1x 10^9 viable rhizobia per gram; the carriers used provide adequate nutrition, optimum pH and oxygen and moisture status so that the bacteria are vigorous and multiplying when inoculation occurs. McInnes and Haq (2003) reviewed the factors affecting the establishment and proliferation of rhizobial inoculants; however, it is difficult to ensure that the added rhizobia will persist in the soil and will fix N effectively (Deaker *et al.* 2004). Biological competition within the soil is fierce and good inoculation can be difficult where there is a pre-existing indigenous rhizobial population (even if it is less effective at nodulation or N fixation). Hence inoculation is most likely to be effective in soils with low indigenous populations of soil biota (Dimkpa *et al.*, 2009).

Similarly mycorrhizal inoculants have been developed – initially for high value ornamental, tree and perennial crops. Hoeksema *et al*. (2010) recently completed a meta-analysis of the factors affecting plant response to mycorrhizal inoculation. They showed that mycorrhizal function depends simultaneously on functional characteristics of host plants, soil fertility and complexity of the soil biotic community. However more than half of the variability in plant response was not able to be accounted for in the analysis (Hoeksema *et al*. 2010), which shows the high degree of conditionality in the establishment of effective plant-mycorrhizal fungal associations.

The development of molecular technologies is increasing the number of effective plant-microbial interactions that have been identified and enabling understanding of their mode of interaction (Berg 2009; Figure A2). Much of the work on these interactions to data has focussed on the understanding of the mechanism and possible isolation of the key organisms involved. Hayat et al. (2010) identify three main modes of action for plant growth promoting rhizobacteria (PGPR) species: i) synthesizing particular compounds for the plants, ii) facilitating the uptake of certain nutrients from the soil, and; iii) lessening the impact or protecting plants from diseases. A number of plant growth promoting fungi (PGPF) have also been isolated belonging to the genera *Trichoderma*, *Fusarium*, *Penicillium* and *Phoma*, etc., have been reported to be beneficial to several crop plants, not only by promoting their growth but also by protecting them from disease (e.g. Shivanna et al. 1996; Harman 2011a).

Richardson *et al.* (2009) noted that plant growth promotion is a complex phenomenon that often cannot be attributed to a single mechanism and may result from the synergistic interactions of a number of species, not only soil bacteria. More work is needed to assess whether the biomass and /or activity of these organisms or the effectiveness of the interaction can be differentially promoted through systems level management. Comparisons of *Trichoderma spp.* abundance under different ecosystems suggests that more intensive land management and lower OM contents may reduce abundance of *Trichoderma* (Okoth & Odhiambo 2009*)*.

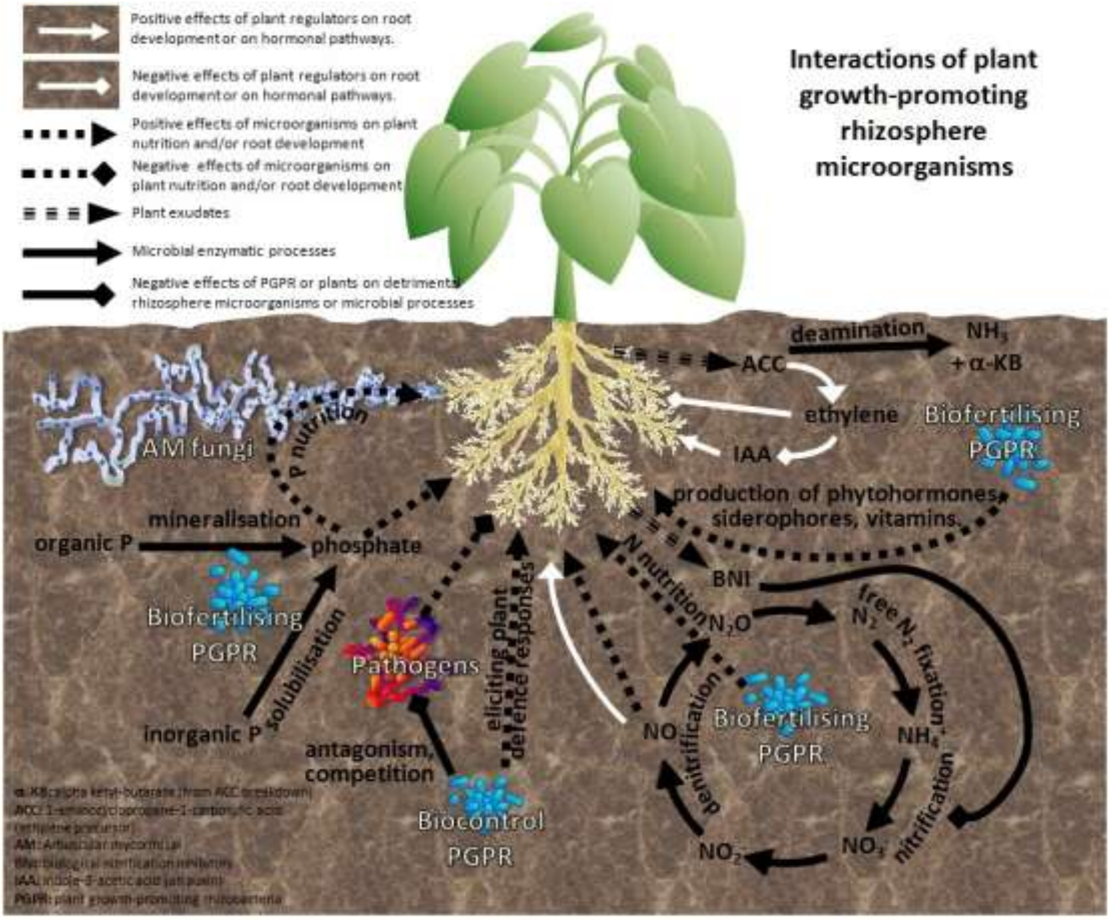

Figure A2 Plant growth promotion mechanisms (positive and negative effects) associated with soil and rhizosphere (PGPR) microorganisms, redrawn from Richardson et al. (2009)

Many reports have documented the ability of soil microbes (such as *Pseudomonas*, *Bacillus* and *Rhizobium* spp., actinomycetes and various fungi such as *Aspergillus* and *Penicillium* spp.) to solubilise insoluble mineral phosphate compounds (Richardson *et al.* 2009). The most common mechanism used by microorganisms for solubilising mineral phosphates seems to be acidification and Ca-chelation via biosynthesis and release of a wide variety of organic acids (Whitelaw, 2000). However, attempts to improve mineral phosphate solubilisation by inoculation with isolated P solubilising bacteria and/or fungi have not been particularly successful because of limitations such as poor ecological fitness, low metabolite production, variability in inoculant-delivery systems, and inconsistent performance in field applications (Shenoy and Kalgudi, 2005; Richardson *et al.* 2009).

There has also been a rapidly increasing interest in biocontrol; strains of *Bacillus thuringiensis, Bacillus subtilis and Pseudomonas fluorescens* are the most important microbials used currently to control insect pests and bacterial/fungal pathogens on strawberries, potatoes, tomato, lettuce, fruit trees, bulbs and turf (Berg 2009). Trichoderma has been known as a fungal biocontrol agent for many plant diseases since the early 20th century although the mechanisms of action were not known. Much or most of the biocontrol activity of these fungi is now considered to be a result of their abilities to induce systemic disease resistance and effective strains also have been shown to convey stress resistance to plants (Harman, 2011b). The basidiomycete *Piriformaspora indica* has at least qualitatively similar effects on plants (Shoresh *et al. 2010*) and hence mixed species approaches might have greater impact. Ardanov et al. (2011) suggest that there may be an important difference between endophytic bacteria which are able to activate basal and inducible plant defence systems and biocontrol strains which have a plant growth promotion effect which is not correlated with induced resistance. Benefits for any crop are mostly strain-specific; hence work is required to screen both bacterial and fungal strains and develop effective inoculants.

Hayat et al. (2010) highlight the widespread availability of PGPR inoculants for a variety of crops (*Azospirillum, Azotobacter, Bacillus, Pseudomonas*, etc.) and show that used alone or co-inoculated with *Rhizobium* sp. these inoculants have resulted in positive responses under controlled (laboratory and greenhouse) conditions. However, Dimkpa *et al.* (2009) highlighted that the successful use of rhizobacteria is dependent on the ability to establish the desired strain in the existing soil microbial community and to enable it to persist. Inoculation at the field scale requires such a large amount of material that is usually considered impractical; successful inoculation at field scale also requires that the inoculums can compete successfully with indigenous bacteria and fungi (Fitter *et al.* 2011). To date there is no evidence of direct effects of inoculation on indigenous soil biota. Studies under field conditions are needed as many of these materials are already marketed commercially. One PGPR preparation has received a lot of attention- this is the mixed microbial inoculum known as 'Effective Microorganisms®' Small differences and often contradictory findings of EM effects have been reported from greenhouse and field experiments. In a detailed study Mayer *et al.* (2010) reported a replicated 4 year experiment testing EM and the EM carrier substrates within an organic crop rotation; they found no effects of EM on crop yield or soil microbial biomass that could not be explained as a result of the nutrient inputs provided in the carrier substrates. Molasses which is a component of the carrier was found to stimulate short-term rates of mineralisation (Mayer *et al.* 2010).

4.0 Studies of interactive effects between agricultural practices on biomass, activity and diversity of soil biota

As indicated throughout this review, implementation of any management practice often involves changes to a number of other practices. For example, changes in crop rotation necessarily lead to changes in tillage type and timing, differences in the amount and quality of residue returns and sometimes implementation of specific targeted measures such as inoculation of a newly included legume species. In terms of impacts on soil biota, interactions between tillage and OM inputs (via plants and/or via organic amendments) seem to be critically important in determining the resilience of the soil biota (Stockdale et al. 2006). For example: the moderating impacts of ley-arable rotations on the long term average biomass of soil biota (van Eekeren et al. 2008); highest species richness of AM fungi occurring under an organic arable rotation rather than species diverse grasslands (Oehl et al. 2009).

More recently some studies have begun to deliberately investigate interactions between tillage and OM inputs.

- Kahiluto *et al.* (2009) studied the roles of fertilisation rate (full mineral, half mineral, organic fertilisation through rotational change), composting (or not) of recycled plant residues and crop/rotational stage in the overall impact of the cropping systems on AM fungi. After the management systems had been in place for 15 years, they found that the low-input system with composting resulted in the highest percentage colonisation by AM fungi. In a bioassay with flax and clover, he AM fungal colonisation in the low-input system with compost gave on average a relative contribution to growth of 27% and to P uptake of 68% in comparison with 4 and 36%, respectively, for the conventional cropping system with full fertilisation. In this low-input system crop yield of rye was 87% of that in the conventional. Where crop residues were not composted there was no significant difference in colonisation by AM fungi between the low input and conventional system. In this study not only the amount of OM inputs but their form (composted or not) had a significant impact on the AM fungi and consequently on the mechanisms of nutrient supply.
- In intensive vegetable cropping, Overstreet *et al.* (2010) showed that where OM inputs were combined with reduced tillage the combination compounded the effects of the treatments individually in increasing nematode populations (compared with intensive tillage and solely mineral fertilisers); in contrast earthworm numbers responded most to tillage reduction and showed little interaction with OM inputs.
- Treonis et al (2010) studied the response of soil microorganisms (bacteria, fungi) and microfauna (nematodes, protozoa) to organic amendment and tillage in cropping systems with tomato/soybean/maize rotations. They showed that organic amendment had positive effects on most measured variables, including organic matter, respiration, protozoan and nematode density, and the abundance of PLFA biomarkers for bacteria and fungi. These effects were more pronounced in the 0-5 cm depth, but most also increased in the deeper layer with amendment, especially with tillage. Increased biomass of microorganisms and decomposer microfauna in amended, tilled soils (0-5 cm depth) corresponded with a decline in the abundance of plant-parasitic nematodes.
- Gil et al. (2011) considered interactions between tillage and crop rotation (soybean monoculture compared with maize/soybean) Total microbial biomass was lowest in reduced tillage-soybean monoculture; species richness of microbial communities estimated by PLFA was increased by crop rotation. Moreover, the fungal

communities, as estimated by DGGE analysis, showed a combined effect of crop rotation and tillage system with higher diversity under rotation and zero till systems.

5.0 Conceptualisation and quantification of ecosystem services delivered by soil biota.

The conceptualisation and quantification of the natural capital associated with soils and the value of the ecosystem services thereby delivered is still at an early stage (Robinson *et al.* 2009; Dominati *et al.* 2010). Within the proposed frameworks, biotic structure (Robinson et *al.* 2009) and soil biological activity (Dominati *et al.* 2010) are included explicitly. Although, links between the biomass, activity and diversity of soil biota and ecosystem function have been mapped to soil functions (Stockdale et al. 2006), quantification of the benefits to function of changes in aspects of soil biota have not yet been achieved . The frameworks are also not at a stage where they can be used easily for the assessment of the expected impacts of key land management practices considered to enhance soil biota for UK farming systems on soil biota and soil function in relation to agriculture and other ecosystem services (even if robust data of impacts were available). There have been some impact assessments of policy change in relation to soil management e.g. Kuhlman et al. (2010) carried out a detailed impact assessment of the application of soil conservation policies in Europe – the costs and benefits at farm and off-site scales of a range of mitigation practices on farm were compared in monetary terms and the least cost-highest benefit practices highlighted. In the future where a small number of recommended practices considered to enhance soil biota for UK farming systems could be identified then such an approach could be applied to inform farm management recommendations. Direct benefits to agricultural systems may be quantifiable though savings resulting from lower fertiliser and pesticide use and reduced fuel use e.g. where soil structure is improved. Off-site benefits e.g. as a result of carbon sequestration or to flood risk mitigation may also be quantifiable.

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APPENDIX 2 – Pre-attendance questionnaire ("My soil story")

MY SOIL STORY

Name and contact details (if you are happy to be contacted later):

My land

Location (e.g. village, postcode):

Soil type and texture of topsoils (if known):

Farming/growing system (description):

Indicate which if any of the following practices you are putting into place (√) or are planning to in the near future (?)

• Use of green waste compost, mushroom composts, paper waste, coffee grounds, treated sewage sludges– i.e. application of (local) waste organic matter	
• Application of biochar	
• Application of seaweed	
• Reduced use of slurry and increased use of solid manures composting	
• Focus on on-farm composting e.g. through more regular turning, monitoring of temperature	
• Developing site specific composts e.g. using inoculation or other additives	
• Vermicomposting	
• Use of compost teas as soil treatments	
• Minimum intensity tillage	
• Non-inversion tillage	
• Overwintered stubbles / late ploughing	
• Permaculture techniques	
• No dig and deep mulching for intensive horticulture	
• Drilling crops directly into clover swards	
• Over-seeding in grasslands	
• Controlled traffic	
• Locally adapted rotations with grass/clover leys	
• Introduction of diverse seed mixes e.g. deep rooting species and herbs	
• Modification of grazing practices; use of some cutting and mulching within grazing systems	
• Targeting inputs of fertiliser and pesticides - precision farming.	
• Reduced use of pesticides (including $CuSO_4$)	
• Not employing soil sterilisation	
• Green manure crops incorporated to provide soil fumigation effects – e.g. mustard	
• Inoculation of legumes through seed treatments	
• Use of mycorrhizal fungal inoculants	
• Use of inter-cropping, under-sowing etc. specifically to enhance mycorrhizal fungi	
• Application of Plant Growth Promoting Rhizobacteria	
• Application of molasses based stimulants for microbial activity	

My soil

What got you interested in your soil life?

Why did you choose the practices you have listed above?

What have been the main difficulties, limits or constraints you've faced?

Have there been any things you've tried that didn't work or that you've stopped? What and why?

What would you want to tell someone thinking of adopting practices to enhance soil life in a similar location / farming system to you?

APPENDIX 3 – Feedback from discussion groups at farmer workshops - experiences of practices

Compiled without summarisation or analysis. Bold text in list of practices indicates additional practice added to the list by farmer groups; bold text in feedback columns indicates identical response in more than one group.

Managing amount and quality of organic matter inputs				
Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Use of green waste compost, mushroom compost, paper waste, coffee grounds i.e. application of (local) waste organic matter.	• **Increase organic matter, biological activity** • **P and K supply** • **Improve soil structure** • **Enhance water retention** • **Reduce diesel use** • **Cheap form of nutrients** • Nutrient inputs • Inoculates soil with beneficial bugs • Supply of trace elements • Improve soil quality • Improve crop quality • Aid fungal development • Seen +3% organic matter in 3 years in stockless system • Provides mulching material • Maintain diversity of soil organisms	• **Recycle nutrients** • Reduce input costs • Fertiliser substitution to reduce costs • Gets rid of waste • Range of materials • Can have liming benefits • Improve workability • Increase crop yields • Sustainable soil structure • Increase window to get onto land • Inexpensive and easy to source (for us) • Long term nutrients • More effective cultivations • Reduce drought stress • Improve nutrient uptake	• **Cost** • **Heavy metals** • **Contamination with plastics** • **Could cause N lock up** • **Risk of compaction on application** • **Risk of introducing weeds** and/or pathogens • Haulage costs • Contamination of land • Availability • NVZ limits • Risk of increasing anaerobic conditions • Don't all break down • Possible Ecoli / Salmonella contamination • Can't measure the benefits easily to weigh against the costs • Waste regulations • Pharmaceuticals in sewage	• **Organic certification** • **Limits to application rates (e.g. NVZ)** • Knowing what is in the materials • Finding out about and accessing local materials • Rates and timing of application difficult to work out • Getting timeliness of application right • Materials should be local or transport costs high • Cost benefit in short term not easy to assess • Getting accurate analysis • Can also be brought in as animal bedding • Is compost PAS100 certified? • Managing mineral imbalances / lock-ups • May be applied only to big fields (> 50 ha)

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Application of biochar		• Reported benefits for carbon storage • Benefits for nutrient holding • Improved structure / habitat for soil organisms • Increase pH • Benefits for water retention	• Cost • Lack of knowledge / information	• **Availability of materials** • UK based supply currently low • Long term sustainability of sources
• Application of seaweed	• **Available as plant tonic** • Source of iodine • Source of minerals • Liming agent • Increase rooting extent and vigour • Fungal feed	• **Good inputs of trace elements** • **Quick hit of plant growth benefit but not long lasting** • Benefit for animal health	• **Very expensive** • Cost • Not sustainable in the long term? • Cheap, if local sources • Ease of application • Certification rules for organic farmers prevent use of some sources	• Availability of material • Localised • Contamination risks • Salt concentrations? • Beach sourced materials need Environment Agency licence • Might only ever be small scale practice

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Mixed methods for on-farm manure handling – reduced direct use of slurry and increased composting	• **Improve C:N ratio** • Higher organic matter • Reduced pollution risk • Composted materials have bigger benefits for long-term soil condition • More soil friendly methods • Increased accuracy of P and K management	• **Reduce pathogens and weed burden** • Less runoff • NVZ benefits • Reduced loss of ammonia • Compost much easier to spread • Create products that are more uniform and easier to manage • Change forms of nutrients – less harmful to soil life • Increase flexibility in use • Increase worms with fresh FYM • More control over materials	• **Fuel costs for handling** • **Timing of application crucial** • Capital cost of modifications to manure handling and storage systems • More handling • May need more straw • Not easy to reduce amounts of slurry produced • Time • Space • Increased labour requirements • Bedding costs	• Spreading • Staying within NVZ regulations • More spreading variability? • How to use manures most effectively in the rotation? • Add slurry to FYM and compost together • Sheet composting on field also possible • Use of inoculants for slurry? • Space to house livestock? Could be more profitable uses of space • Issues with preventing rain ingress • If handling liquids then specialist injection may be needed

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• On farm composting using a range of advanced techniques to develop site specific composts	• Tailor compost to crop need • Targeted applications in time and space • Reduce carbon footprint • Can add minerals into compost heap and hence increase soil availability • Most advanced methods for waste handling	• Direct benefits to crop yield and quality • Build soil organic matter • Greater nutrient retention in the farm system • Need to develop appropriate propagation substrates • Greater consistency • Greater biological activity in soil	• Capital cost of modifications • Cost • Lack of technical know-how • Scale • Time	• Space • Time • Risks not well identified • New skills needed • Do you need to turn with a dedicated machine? What about loader or spreader? • Not practically possible – "a dream" • Lack of animal manures if no livestock on farm
• Vermicomposting	• Breaks down OM quicker • Rich source of crop available nutrients	• Reduce volume of waste • Manipulate materials nutrient availability • Soil improver • Recycles waste products • Liquid feed is high in available nutrients	• Is it cost effective? • Suited to small scale, may not be appropriate to farm scale • Increased disease potential • Increased risk of weed seed transfer	• Space • Time • Worm availability • Not well demonstrated at farm scale • Keeping worms alive! • Should be assessed as adding an additional enterprise to system
• Use of compost teas as soil treatments	• **Use to inoculate soil with key organisms** • **Increase soil microbiological diversity** • Benefits to plant health • Reduce pathogen damage		• **Lack knowledge** • Capital cost of equipment • Difficult to make on site • Complex • Too whacky! • Unproven benefits • Benefit on ordinary soils unlikely •	• Appropriate application machinery • Needs very good sprayer hygiene • Need to develop specifically for your requirements • Good for foliar treatments

Modified tillage practice				
Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Minimum intensity tillage includes non-inversion tillage	• **Less compaction** • **Improve structure** • **Less soil disturbance** • Reduce soil damage • Can lead to increased smearing and weak structure • Increased grass weeds • Keep OM on the surface • Better drainage • Better travel over the field • Improved worm counts • Better soil life	• **To reduce diesel consumption** • **Increased OM at the very top of soil** • **Quicker than ploughing** • Benefit soil organisms • Better response to inputs • Increase yield • Reduce capital costs • Protect soil structure • Improve timeliness • Keeps microbial activity and nutrient release closer to surface for roots • Doesn't upset soils • Saving in labour	• **Weed control** • **Soil specific requirements** • **Getting the right machines** • Increased blackgrass in conventional systems • Increased problems with sterile brome • Really difficult in organic systems • Need to invest in new equipment • Management more complex – do farm managers have time? • Can lead to more compaction • Can't bury trash and hence can increase disease transmission risk in some rotations • Soil should be in good condition first	• **How to establish when rotations include ley and hence need to break sod.** • **Non-inversion may need more passes to get the same effect** • **Timing critical** • Perceived to be reliant on herbicide inputs – how true? • Transition period is difficult • Balance of slugs, beetles etc • Crop failure is system failure – not or weather/ year etc • Improves ease and access for timely cultivation • Slug control • Not on all soils? • Weather conditions matter more • Not suitable for heavy soils

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• **No till**	• Fuel saving • Soil protection • Conserve and enhance soil OM		• Uncertainty • Unknown • Looks scruffy	• Smaller/ fewer tractors • Don't get tempted to plough it takes time, keep the faith • British Farming Forum website has good set of discussions from practitioners of zero till
• Controlled traffic	• **Reduce compaction for most of field** • Minimise yield loss due to compaction	• Fuel saving • Improved timeliness	• **Difficult to set up** • Compromised from ideal by implement widths • Need to match machine widths carefully • Cost • Hard work to manage • Wheeling spacing of machinery often not identical	• Increased labour requirements • Weather restrictions
• Use of livestock grazing to reduce cultivation		• Save diesel • Effective interaction of crop and livestock		• Pigs in arable systems • Pigs / very heavy stocking ahead of ley cultivation • Can cause problems with compaction

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Overwintered stubbles	• **Soil protection in autumn** • **Green cover** • Entry for spring cropping • Good for birds and wildlife • ELS points • Reduced erosion risk • Less runoff • Longer window for weed control with herbicides	• Provides window to apply soil amendments • Less pressure on the farmer • Some overwinter grazing possible • Retain nutrients	• **Difficult to get access for spring cultivation** • Difficult to make good seedbed in spring • No opportunity for frost to breakdown soil • Erosive losses in spring • Reduced yields • Not practical in potato systems • Land is not actively growing for you – wasted opportunity • Invasive weeds can become a problem	• Why not drill into the stubble? • Better seed bed • Need to kill volunteers • Not practical on heavier soils • Field choice important • Soil specific
• Drilling crops directly into clover swards	• Soil protection • Low energy use • Take advantage of fixed N for crop • Reduced cultivation costs • Permanent ground cover	• **Weed control** • **N fixation supplies N to crop** • Disease control • Good way of adding goodness to soil • Increasing beneficial insects • N inputs reduced	• **How can competition with crop be best managed?** • Slugs • Not known about or understood • Clover easily gets out of hand • Didn't see benefit for partner crop • Not tried and tested	• **Is specialist equipment needed?** • Limited practical evidence • Can use sheep grazing to holdback clover sward • Persistent perennial weeds can become established

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Permaculture techniques	• Could increase resilience though diversity of cropping	• More production (calories) per hectare	• **Not practical at a large scale** • Complex to manage • Root crops out at large scale • Increased between crop competition for sun, water etc need to be thought about carefully.	• Very complex to establish and manage • Suited to owner-occupier system due to long-term benefits
• No dig and deep mulching for intensive horticulture	• No soil disturbance • Maintain natural soil structure	• Weed control • Improved crop yields • Better crop health • Reduced energy use • Good for early cropping • Reduces waste	• **Finding a good quality mulch** • Heavy demands on compost • Cost of materials to compost to provide mulch • Bulky to transport • May be contamination issues	• Hard to determine cost – benefit balance • Suitable at small scale – not sure it can be adapted to use on hectares

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Overseeding in grasslands	• **Cheaper than whole reseed** • Improve/ maintain clover content • Improve sward with minimal disturbance • Increased yield	• Maintain soil structure • Low energy • Reduces poaching • Reduce diesel use • Increase productivity • No lost production time while improving grassland • Enrich pasture diversity	• **Hit and miss results** • Establishment can be poor and patchy • Need suitable drill • Increases weediness • More risk – increased risk of poor establishment if stitching in clover to existing sward • Need more clear guidance about when/ how • Waste of expensive seed • Success very weather dependent • *"Many of costs, only ½ the gain"*	• Compaction may need to be reduced before these techniques can be successful • May need to seed into a scratch so there is soil contact • Use of tined weeder to open up sward before overseeding • May need to seed with aggressive species to make it successful • Quality of existing swards
• **Aeration of grasslands**	• Reduce compaction • Increase aeration • Reduce runoff	• Rejuvenate existing pastures		• Could be linked with overseeding • Best followed by FYM/ compost application
• **Winter feeding to extend grazing**		• Spreading out grazing impacts	• Often creates bare patches allowing weed invasion • Increased risks of runoff • Poaching	• Placement of feeders • Need to move feeders during winter can cause soil damage

Changes in crop rotation/management				
Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Locally adapted rotations with grass/clover leys	• Clover content in seed mixes may be adapted to location • Use combined crops e.g. oats& peas, peas and barley, lupins and triticale. • Look at traditional practices in the locality but try new options • Match to local climate important	• Achieving nutrient balance • Increase livestock growth rates with good clover levels in swards • Sustainable cereal production • Disease breaks • Make full use of the N fixed by the clover ley • Fertility balance • Soil structure stable • Fitting crops to soil type • Reducing risk across whole farm	• More adopted in organic situation. • Need to manage cows more carefully on clover rich swards (bloat risk) • Oats and peas often don't have as good a feed value as expected • Getting access to the local knowledge needed • Adds complexity to management	• Best if in mixed systems • Red clover best if only 1 in 6 years to minimise disease risks • Undersow to establish clover earlier • Length of rotation may be determined by weed burden • Poor returns from livestock enterprises make mixed systems less attractive

• Integration of green manures into crop rotations	• Species highlighted
	  ○ Mustard
	  ○ Phacelia
	  ○ Oats
	  ○ Grazing / cereal rye
	  ○ Range of legumes
		• **Weed suppression**
		• **Overwinter cover**
		• **Better soil structure**
		• **Increase organic matter**
		• Easy to do
		• Choose cheap seed
		• Freshen the soil
		• Good for wildlife
		• Structure improvement
		• Holding on to nutrients
		• Pest and disease control
		• Less weather prone
		• Larger and more diverse root mass
			• Cost of seed
			• Timing not always right
			• Additional cultivations
			• Problems if persists – so don't let mustard flower!
			• Hassle
			• Feed value not well understood
			• Can tie up nutrients
				• Frost kill
				• Need to match species to rotations and soil
				• Can provide early bite if needed
				• Can also graze spring wheat to encourage tillering
				• Winter grazing can lead to big poaching risk

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Introduction of diverse seed mixes e.g. deep rooting species and herbs	• **Improve soil structure** • **Bring up minerals from deeper soil** e.g. K • Improve soil fertility/ rooting depth • Reduce compaction/ work together with mechanical improvement to maintain effect • Chicory in the sward has worming effect in lamb • Improve biodiversity • Drought resistance	• **More balanced/diverse diet for grazing livestock** • More drought resistant • Pull up more minerals • Introduce more varied N fixers • Improved animal welfare	• Cost of seed • Chicory is very expensive and lack of information about benefits • Takes more management • Not always reliable	• Slow to establish but better in long-term • Some species may be too vigorous if not managed carefully • Not all mixes suit conservation e.g. chicory • Is good range of seed available? • Mixed fodders might be better introduced as whole crop silage • Managing mixed swards for grazing needs more care • Constrained by the organic rules on % organic seed
• Modification of grazing practices; use of some cutting and mulching within grazing systems	• Weed control • Re-invigorates growth	• Keeps more diverse sward • Feeds more soil organisms • Good for controlling thistles • Clean ground to minimise pathogen transfer between livestock • Reducing weed burden	• Can be difficult to fit with farm needs • Need to keep swards on drier ground for winter • Can increase vulnerability to drought • Increases labour requirement to manage temporary fencing • Cost – need the feed value	• Long rotation mob grazing also has above ground benefits • Reduced need for herbicide • Mixed species grazing has benefits for utilisation efficiency • Changes in grazing patterns can interact with wildlife benefits

Specific targeted interventions				
Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Targeting inputs of fertiliser and pesticides precision farming	• **Lower application by increasing specificity** • **Reduce variable costs of inputs** • More effective use of P and K by placement and timing • Less concentrated applications = less osmotic damage • Reduce impacts on the environment of use	• Site specific fertiliser applications create more uniform soil condition • Saving of waste • Targeted use of salt makes docks palatable and increases sward palatability in urine rich areas (where K high)	• **Costs of guidance equipment** • Operators need to be trained and willing • Lack of knowledge on benefits • Added complexity	• Promoted by catchment sensitive farming and fertiliser salesmen • Many folk are trying – may be zoning within paddocks or full GPS • Confidence in the technology • Needs good knowledge of underlying soils to target inputs
• Reduced use of pesticides including $CuSO_4$	• An indirect outcome from adoption of min till • Improve margins and biodiversity		• Fear of consequences for yield • For conventional pesticides care with regard to development of resistance	• De-tox needed when converting from conventional to organic
• Not employing soil sterilisation			• Weed persistence • Soil-borne disease	

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Green manure crops incorporated to provide soil fumigation effects – e.g. mustard	• To reduce weed germination • Allelopathic effects	• Might also increase nutrient mobilisation • Reduce beet cyst nematode	• Don't know about role as soil fumigant • Not enough information about managing the timing between crops	• For min till into a sod mustard can be used. Graze hard then overseed with mustard (grow 1 month- 6 weeks) then disc and seed e.g. autumn turnip
• Inoculation of legumes through seed treatments	• **To increase lupin establishment** • **To improve establishment of lucerne** • With clover (occasionally) • With sainfoin but didn't grow well	• **Increased N fixation** • Crop survival • Improved nodulation	• Knowing whether organisms are in the ground already • Cost • Another thing to remember to do – easily forgotten	• Hard to know if it was really needed and what benefit really was • All fields seem to respond differently • Little practiced • Information of effects limited • Can buy seed with inoculant already mixed
• Use of mycorrhizal fungal inoculants	• To balance fungal part of foodweb • Improve uptake of P and micronutrients	• After intensive cropping and inputs to encourage re-establishment • Because they are missing from highly worked soils • To improve field with low productivity	• If they are already there, but no easy test? • Cost • Lack of response if high P	• **Does it make a difference?**

Practices	Expected impacts	Why do it?	Why not?	Other practical considerations
• Application of Plant Growth Promoting Rhizobacteria				• Highly technical • Not readily available in the UK
• Application of molasses based stimulants for microbial activity	• Promotes bacterial growth • To increase nutrient cycling • Quick stimulation	• Better breakdown of manure • Encourages the right bacteria when applied in silage pit • To improve soil biology	• Agrochemical spray people not keen as it "muddies" the effect of their products • Cost • Information on cost effectiveness not readily available • Available in organic systems? • Short term effect	• Seems to increase the effectiveness of sprays when co-applied – doesn't drift as much. • Used as silage stimulant • Rate of use not well understood • Difficult to spray
• Application of gypsum	• To add Ca • To promote improved soil structure	• Not expensive	• There are many claims for benefits but no clear evidence except in saline soils • Using stimulants when there are serious problems – but how do you know when it is safe to stop ???	• Need to ask for Ca specifically on soil testing

APPENDIX 4 – Case studies of on-farm practices to enhance soil biota

See Annexes 1 - 5