Natural England Commissioned Report NECR100

Managing soil biota to deliver ecosystem services

Summary document

First published 04 October 2012

www.naturalengland.org.uk

NATURAL ENGLAND

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

Many recent studies have highlighted the fundamental role that soil organisms play in making soils work for us, but also suggest that soil life and its function can be compromised by many commonplace agricultural practices. This report aimed to explore how farming practices and systems could improve the biological function of soil, and deliver benefits to both agriculture and the wider environment. It includes a review of the impacts of different practices, an exploration of selected practices likely to deliver benefits, feedback from farmers' workshops on the practicalities of different approaches, and also five case studies (as separate Annexes) which describe soil biological management in action, its benefits and challenges.

The report concludes that the biological function of soils can be enhanced by simple approaches that can be integrated into real farm systems - adapting organic matter management, cultivation approaches and cropping - with likely benefits to both farming and the environment. However, uptake of these approaches was restricted by the lack of UK-based demonstrations, trials and advice, and because it is currently difficult for farmers to measure and evaluate impacts on soil biological health. The report highlights an opportunity to communicate and demonstrate these approaches in real, profitable farm systems, with monitoring of the impacts, costs and benefits.

Natural England Project Manager - Matthew Shepherd, Renslade House, Bonhay Road, Exeter, EX4 3AW **matthew.j.shepherd@naturalengland.org.uk**

Contractor - Elizabeth Stockdale, School of Agriculture, Food and Rural Development, Newcastle University, Newcastle upon Tyne, NE1 7RU **elizabeth.stockdale@ncl.ac.uk**

Keywords - Soil biota, ecosystem services, soils, agriculture

Further information
This report can be downloaded from the Natural England website: **www.naturalengland.org.uk**. For information on Natural England publications contact the Natural England Enquiry Service on 0845 600 3078 or e-mail **enquiries@naturalengland.org.uk**.

ISSN 2040-5545

A full version of this report can be found at NECR100 - Managing soil biota to deliver ecosystem services

Project team

- Christine Watson, Crop and Soil Systems Group, SAC.
- Julia Cooper, Nafferton Ecological Farming Group, Newcastle University.
- Phil Stocker, Director of Farmer and Grower Relations, Soil Association
- Stephen Briggs, Abacus Organic Associates and Director of Institute of Organic Trainers and Advisors.
- Stephen Roderick, Rural Business School, Duchy College.
- Luppo Diepenbroek, independent consultant and farming group facilitator (SW England)
- Adam Twine, Colleymore Farm; Founding director of The Farm Carbon Cutting Toolkit community interest company (FCCT)
- Ron Stobart, NIAB TAG

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.