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## Evaluating the soil health scorecard approach: monitoring innovations in management of soil biology and health already in place on farm

Elizabeth Stockdale[1], Christine Watson[2], Paul Hargreaves[3] Chris Stoate[4], Dominic Amos[5] and Anne Bhogal[6]

[1]NIAB, 93 Lawrence Weaver Road, Cambridge, CB3 OLE
[2]SRUC, Craibstone Estate, Aberdeen, AB21 9Y
[3] SRUC, Barony Campus, Parkgate, Dumfries, DG1 3NE
[4]GWCT, The Allerton Project, Loddington, LE7 9XE
[5] The Organic Research Centre, Trent Lodge, Stroud Road, Cirencester, GL7 6JN
[6]ADAS Gleadthorpe, Meden Vale, Mansfield, NG20 9PD

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# 1. Abstract

As part of the work within the Soil Biology and Soil Health (SBSH) Partnership, this project worked with farmer groups across the UK to evaluate the use of the Soil Health scorecard approach to give a ‘snapshot’ overview of soil health on a rotational basis by integrating chemical, physical and biological indicators (developed in an earlier SBSH Partnership project, Project 2). The SBSH Partnership also worked closely with advisers and the wider agricultural supply chain to draw together and build on their knowledge and experience to create accessible tools and guidance.

An open process was used to recruit farmers from a range of farms and farming systems across the country with diverse climate, soil types and rotations. Up to 100 farmers worked together in 8 farmer innovation-research groups during the SBSH Partnership and these included growers confident that they were implementing soil-improving management practices, together with those who were not sure that their actions were positive for soil health. A range of practices, mainly system-oriented approaches, had been adopted (i.e., increasing OM input, reducing tillage intensity, increasing cropping/sward diversity) but there were also tactical interventions, such as slurry inoculation, application of molasses or compost teas, companion cropping and controlled traffic farming (CTF) systems. Each farmer-research innovation group sought to contrast the impacts of different or changed management approaches on soil biology and health (2018-2021) extending the range of treatments studied in the trials in work package 2 (Projects 4 and 7). The SBSH Partnership also worked closely with the AHDB Cereals & Oilseeds Monitor Farms from autumn 2019 and other farmer groups outside the SBSH Partnership to pilot the Soil Health scorecard approach.

The farmer innovation-research groups found the field protocol relatively easy to follow, especially when demonstrated visually (including as a video reminder). Within farms, farmers used their knowledge of the differences in inherent soil properties to select sampling sites. For many farmers the intention was to select sites that would continue to be monitored in the future alongside other targeted sampling e.g. for nutrient management or tillage optimisation. The farmer groups confirmed that although the timing of sampling when soils are moist and warm (mid-autumn / early spring) fell in a busy period, it could be implemented in practice. Across all groups, the most common rotational crop was a first cereal (often, but not always winter wheat). The groups sampling in cropping systems therefore sought to match their sampling across the group to post-harvest in the stubble or cover crop after a cereal and after the soil had wetted up (usually October/November), to allow the most effective benchmarking between fields/farms. When the principles and the protocol were described to growers in perennial row crop systems, they were able to rapidly adapt and then apply the new protocol effectively. Over 80% of farmers were able to complete both field data collection and sample submission. As part of, or working with, the SBSH Partnership, 287 Soil Health scorecards were collected on farm between 2018 and 2020 across a range of farm system and soil types, together with 22 sites in orchards.

Farmers liked the overall Soil Health scorecard which integrates physical, chemical and biological aspects to give a snapshot overview of soil health - akin to a routine car safety check (MOT) or school report - and confirmed that it gave a useful visual health check. Farmers particularly valued the visual evaluation of soil structure (VESS) scoring and considered that capturing photos provided a clear record. Overall, consultation and review supported the use of the multi-factorial framework and no indicators were removed. The work in Project 12 and here confirmed that adding an indicator of microbial activity to the Soil Health scorecard potentially gives some additional detail on soil function at relatively little extra cost. However, care is needed to interpret and use the data especially $CO_2$-burst for calcareous soils. Review of the indicators with the data collected in the project has led to:

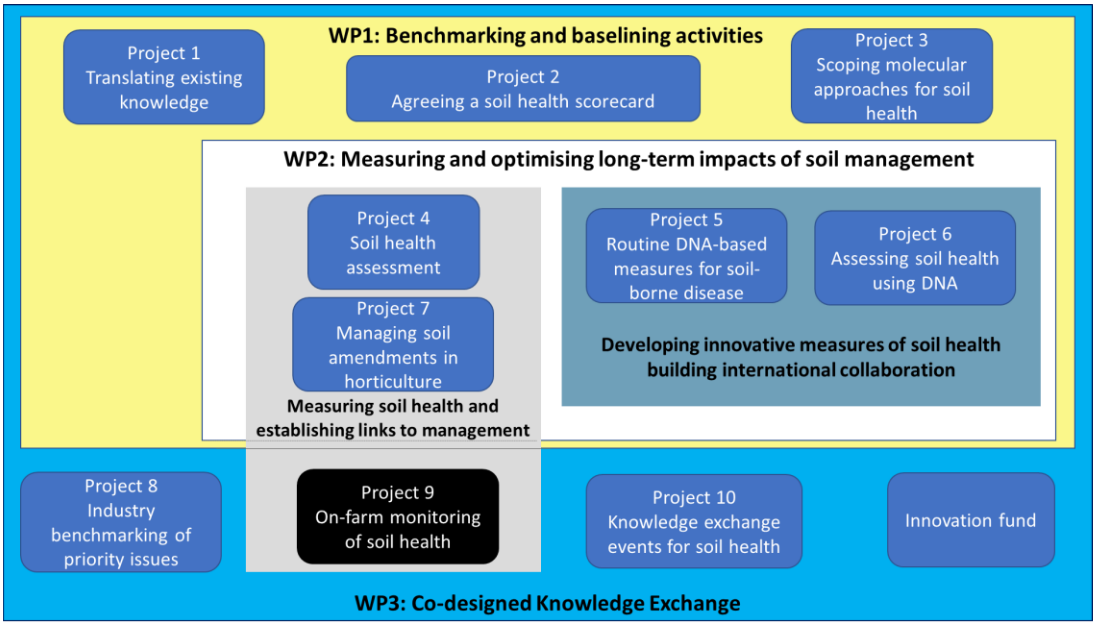
- Reduced thresholds for the earthworm number benchmarks in grassland.
- Strong confirmation of the value to farmers and advisors in providing simple benchmarks for soil organic matter (SOM); minor updates were made in the presentation of the benchmarking tables compared with those presented during the project for consultation.

Farmers recognised that just knowing some numbers about soil, even having an integrated assessment of physical, chemical and biological properties with comparison to relevant benchmarks won't improve soil health. In the project, the Soil Health scorecards collected by the farmers supported informed discussion within and across farmer innovation-research groups about the range of soil management practices already used, and the practices that might be adopted to maintain/ improve soil health. In particular, the groups valued the way the presentation of data within the Soil Health scorecard quickly identified areas where improvement can be made through management or where more detailed assessments or more regular monitoring are needed to clarify the problem. Overall, the discussion with farmer innovation-research groups highlighted that although general guidance is useful to inform practice choice, the best soil husbandry is always site and season-specific, and each action needs to be informed by observation. Farmers also valued the evidence emerging from research trials of links between improved soil health (or soil-improving practices) and increased yield (Project 4). However, farmers quickly recognised that even within a farm or farmer innovation-research group, it was difficult to separate the impacts of season, inherent soil factors and soil health on on-farm yields. Now that the Soil Health scorecard is in place, it should be possible to integrate its use into other studies e.g. looking at achievement of yield potential, yield resilience and/or the delivery of other ecosystem goods/ services. Such approaches should enable an increased understanding of the links between land management, soil properties and soil functions, with appropriate consideration of spatial and temporal distribution, in order to optimise the delivery of all ecosystem services in the landscape.

## 2. Introduction

This project (Project 9 of the Soil Biology and Soil Health (SBSH) Partnership) aimed to measure the impacts of the broad range of innovations in management of soil health already present on commercial farms by working with farmer/grower groups to collect and collate measurements of soil health and, where possible, link these measures to data on crop yield/ quality. It is part of a suite of integrated projects within the SBSH Partnership (see diagram below showing how this project fits into the wider organisation of projects). This work built on the development of a scorecard approach to soil health assessment designed for use on a rotational basis (Project 2) which integrated a number of chemical, physical and biological indicators to give a 'snapshot' overview of soil health (akin to a car MOT or school report), designed for use on a rotational basis to be repeated in the same field location. Project 9 was conducted within Work Package 3 (WP3) of the SBSH Partnership which brings together Projects 8, 9, and 10. The overall aim of WP3 was to ensure that the SBSH Partnership worked with a strong focus on two-way delivery of knowledge exchange (KE) throughout, ensuring research groups were fully aware of industry needs, were able to respond to and work with industry in the development and delivery of research and that the outputs were effectively disseminated to industry during the lifetime of the SBSH Partnership. Ongoing farmer innovation and KE activities (Projects 9 and 10) provided regular opportunities for industry to highlight emerging research priorities not captured initially and shape the direction of the research. Projects 4, 7 and 9 were also closely linked; each used the soil health scorecard approach developed in Project 2 to quantify soil health in long-term experiments (Project 4), experiments using soil amendments in horticultural crops (Project 7) and for on-farm monitoring (Project 9).

Project 9 shown (in black) within the integrated project delivery of the Soil Biology and Soil Health Research and Knowledge Exchange Partnership



## 2.1. Objectives

Farmers and growers already use a range of innovative approaches for the management of soil biology and health, often combining a number of the strategies investigated in AHDB research projects and integrating new approaches that are adapted for site-specific use (as shown in Stockdale and Watson, 2012). This network of farmer research and innovation can deliver important information to inform both research and practice through participatory approaches to evaluate the impacts on soil biology and health across a broad spectrum of crops, climates, soil types and rotations. Therefore, as part of the SBSH Partnership, this project worked with farmer/grower groups to collate measurements of soil health made using the soil health scorecard developed in Project 2 and, where possible, link these data to impacts on crop yield/ quality. The overall aim of this project (Project 9) was to measure the impacts of the broad range of innovations in the management of soil health already present on commercial farms. The data set also provides background context against which the development and roll out of new tools for soil health can be interpreted to develop appropriate guidelines for the industry.

The specific objectives of Project 9 were:

1) Establish 6-8 farmer-research innovation groups (8-15 growers per group) that link up a wide range of farms and farming systems across the country (encompassing a diverse range of climate, soil, rotations) during autumn/winter 2017.
2) Support the use of a soil health scorecard approach (developed in Project 2) to ensure that it provides farmer-friendly soil assessment together with management data to collect a soil health dataset that can be linked to crop yield constraints within on-farm rotations (2017-2020).
3) Work with at least one farmer in each group to compare / contrast different management approaches alongside their normal practices that dovetail and/or extend the range of treatments studied in the trials in WP2 (Project 4 and 7) and collate data on impacts of changed management on soil biology and health (2018-2021).
4) Collate the data from all the farmer-research innovation groups and test and develop the descriptive model developed in Project 1.
5) Work with the farmer groups to develop a range of appropriate KE materials drawing from these on-farm studies and the outputs of all the research projects of the SBSH Partnership

## 2.2. Background

Achieving optimum yield potential and managing fixed and variable costs are essential factors in any profitable farming business. Sustainable soil management is central to the delivery of economically and environmentally sound, resilient and productive cropping. Soil physics, chemistry and biology are interlinked, and all play a role in maintaining productive agricultural and horticultural systems. At landscape scale, soils are also expected to provide a broader range of ecosystem services simultaneously. The Food and Agriculture Organisation has defined soil health in relation to key soil functions as: "*the capacity of soil to function as a living system, within ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production*" (FAO, 2008). Improving/securing soil 'health' has therefore been discussed increasingly, with the assessment of soil health essential for informing decisions on soil and nutrient management in order to maximise crop yield and quality, whilst minimising production costs. Improved soil health will also lead to environmental benefits by increasing nutrient use efficiency, which will reduce agriculture's environmental footprint by minimising multiple diffuse pollutants to air (i.e., nitrous oxide emissions) and water (e.g., nitrate, ammonium, phosphorus and sediment). Improved soil structure can also increase the rate at which water infiltrates into soil and thereby reduce the risk of overland flow and flooding during high rainfall events. The SBSH Partnership aimed to expand the knowledge base on soil health to improve grower understanding and also to identify practical approaches that can be utilised relatively easily, allowing famers and growers to increase soil health whilst maximising crop yields and quality in rotations that include grassland, arable and horticultural crops.

While farmers/ land managers are expected to be important end-users of approaches to soil monitoring, to date, they have generally played an insignificant role in the development of assessment schemes for soil health; the initiation and development phases have been dominated by scientists and policy /government agencies (Bünemann *et al.* 2018). In the United States the focus has been on the empowerment of land-users to measure soil quality for themselves and then to implement changes in practice. The Natural Resources Conservation Service provide information about in-field tests that can be carried out by land-users together with further details about a range of further tests and their interpretation (NCRS 2014). The Soil Management Assessment Framework (SMAF) developed at the Soil Quality Institute (Andrews *et al.* 2004; http://www.soilquality.org) allows users to select a set of indicators depending on intended soil function(s). In contrast, the Cornell Soil Health Test (Idowu *et al.* 2008) is much more standardised, but is also targeted directly at land users, offering various soil health testing packages and supplying management advice together with the results. In this project, the project team sought to take a proactive role ensuring that the perspectives of all stakeholders were included so that the range of approaches taken to measure and manage soil health for UK agricultural systems is complementary by including interactive design and decision-making with end users throughout the development and evaluation stages.

To allow control of the factors under study, research trials often have specific and narrowly focused remits; data collected in trials therefore allows robust assessment of the impact of individual drivers of biological activity (see Project 4). In contrast to experimental field trials, farmers' field management is often dynamic, with multiple management practices implemented season to season over several decades based on a range of practical considerations, e.g., farm labour, machinery requirements etc. that are tailored to specific fields. This diversity and seasonal variation in practice can limit the applicability of the findings from research trials into practice. Farmers also have significant local knowledge of their fields (or management zones) and may label them as "good" or "poor," by taking agronomic performance and local soil knowledge into account. Aligning farmers' knowledge of soil characteristics and function alongside the interpretation of the results of soil health tests is important for the implementation and adoption of soil health management practices. Knowledge exchange work on-farm regularly highlights that there are a significant minority of farmers already investing in the development of techniques to improve soil health by taking up practices which require more of their time, and which may also have required significant capital investment. Practices that affect soil health are adopted on-farm for several reasons, including economic or management drivers, as well as a concern for soil function, consequently there is a need to provide breadth of information that can be used to guide uptake and assess cost-effectiveness in the local context.

Following the launch of the UK government's 25 Year Environment Plan (HM Government, 2018) and the move away from the EU's Common Agriculture Policy after Brexit, a wholly new policy approach for the agricultural industry is currently under development, and this will include schemes and advice to support improved soil management on-farm (Defra, 2021). It is important to note that the work of the SBSH Partnership was carried out separately to the development of schemes and advice streams by Defra and its agencies.

# 3. Materials and methods

## 3.1. Establishment of farmer-research innovation groups

With the SBSH Partnership, Project 8 took a co-construction approach to the benchmarking of current knowledge and experience through a series of workshops with the agri-food industry, including advisors, famers and growers. Project 8 actively sought to elicit interest in participation in farmer-research innovation groups to link up a wide range of farms and farming systems across the country (encompassing a diverse range of climate, soil, rotations). Existing GREATsoils project groups working in horticultural systems in collaboration with the Organic Research Centre were also followed up. An on-line registration process was launched via the AHDB website overwinter 2017/18. Expressions of interest were screened in relation to the location, number of engaged farmers, main farming systems covered by the group and links to SBSH partners or external projects.

A series of project initiation meetings was held regionally in spring 2018 with all key farmers/ growers/ advisors expressing an interest in facilitating a farmer-research innovation group. The meeting discussed the experiences of farmers/ advisors in on-farm innovation in the management of soil health across a range of sectors including grassland, cereals and oilseeds, potatoes, sugar beet and vegetables. At this meeting, the scope and shape of the research programme within WP2 of the SBSH Partnership was presented and the potential groups reflected on how these interventions related to the on-going work on the farms that are represented by their group. The requirements for the on-farm network to include a wide range of farms and farming systems across the country (encompassing a diverse range of climate, soil, rotations) and the project expectations with regard to on-farm monitoring (using the tools developed in Project 2) as well as the support available and opportunities for the groups were discussed in detail. It was expected that farmers would also benefit in terms of knowledge gained and practical experience of seeing a range of techniques in practice, as well as working directly with the research team; this may have been perceived as a benefit or a cost by the farmers! The aim was to establish 6-8 groups, engaging directly with 75-100 farmers and advisers involved in, or interested in, implementing innovative management practices to enhance management for better soil health.

### 3.2. Research and development within farmer-research innovation groups

On-farm meetings were arranged for September/ October 2018 to walk through the proposed sampling protocol for the soil health scorecard developed in Project 2, and updated following discussion with advisors, famers and growers during the workshops in Project 8. At these initial meetings, each farmer-research group developed a proposal for their monitoring strategy for 2018-2021 to include robust baseline data on soil health collected on-farm in fields across key parts of the farm rotation, including where appropriate cereals, oilseeds, sugar beet, potatoes, field vegetables, grass and cover crops. The intention was to collect a broad data set (though not as detailed as the data collected for the experimental sites collected in Projects 4 and 7) that would add significantly to the coverage of soil types, crops and climates for which data were collated within the SBSH Partnership, and which provide a wider context to the findings of the detailed research projects and support evaluation of the descriptive model developed in Project 1. Each farmer-research innovation group sought to compare / contrast different management approaches that dovetailed with and/or extended the range of treatments studied in the trials in WP2 (Project 4 and 7) and to collate data on the impacts of changed management on soil biology and health (2018-2021).

In each year, a sub-set of farmers from the research-innovation group carried out soil health scorecard assessments, including field assessment of soil structure and earthworm numbers, as well as collection of soil samples for laboratory analysis. Soil sampling took place in the autumn post-harvest and after the soil had wetted up with a focus on using paired field comparisons/ split field treatments. In the first year the focus was on evaluation of the sampling requirements and in-field recording of visual evaluation of soil structure (VESS) and earthworm numbers with a small number of chemical and biological measurements (pH, P, K, Mg, Ca, Na, soil organic matter) made on the bulk soil samples collected. Further measures of soil biological activity ($CO_2$-burst, potentially mineralisable N) were added from 2019.

Each of the farm-research innovation groups then met in the late winter (usually February) to review their experiences, discuss the data collated, explore implications for management on-farm and to provide critical input to data interpretation emerging from the other projects of the SBSH Partnership. These inputs were used to evaluate the soil health scorecard approach and to update protocols, measures and interpretation as required. These meetings also reviewed the monitoring plan for the coming season and adjusted it, as required by the group.

The programme of on-farm engagement was enhanced by the active adoption of the soil health scorecard approach by the AHDB Cereals & Oilseeds Monitor Farms from autumn 2019. Other farmer groups from beyond the Partnership also worked closely with the project team to pilot the soil health scorecard approach:

- the Wallop Brook Farms' cluster, led by the Hampshire & Isle of Wight Wildlife Trust, enabled by funding from the Countryside Stewardship Facilitation Fund (2019-2020);
- the Sainsbury's Grower Interaction Group for top-fruit (2020-2021).

Due to COVID-19 restricting face-to-face interactions significantly, the programme was adapted from spring 2020 onwards with the use of more on-line meetings and some one-to-one or one-to-small group meetings used during the final phase of the project where broader cross-group interactions had been planned initially.

### 3.3. Integrated review to increase the understanding of the effectiveness of management options for soil health

During 2021, the project team used the data collated across the farm-research innovation groups to provide a further evaluation of the descriptive model developed in Project 1 and reported in Project 6. In addition, the data collected from the farm-research innovation groups was used and farmers discussed their experiences to add to the understanding of the effectiveness of a range of management options for soil health, including the effect of options on soil structure, fertiliser and water use, crop yield and quality and impacts on soil function at landscape-scale e.g., flood mitigation. Where possible, the on-farm implications of the range of land management practices were also explored; this included a qualitative evaluation in terms of farm labour, machinery requirements etc.

Engagement with the industry during the SBSH Partnership was not restricted to the interactions with the farm-research innovation groups. A number of approaches was used flexibly and actively to work with farmers, growers, advisors and industry partners to shape the development of a soil health toolkit and to enable wider work on the management of soils in agricultural systems to maintain and improve soil health. Open workshops were used at intervals to add breadth and depth to the viewpoints, concerns and proposed solutions developed within the SBSH Partnership team, which is already multi-stakeholder in composition. This wider engagement also provided key insight and experience as part of the review of management options for soil health. In summer 2020, the SBSH Partnership held a workshop with key academics working in soil health, the main soil testing laboratories and current soil health information providers, mainly the large agronomy companies, specifically to review the presentation and benchmarking for the Soil Health scorecard.

### 3.4. Data review and descriptive analysis

All the Soil Health scorecard data were collated in Excel for review. To support the review of the presentation and benchmarking for the Soil Health scorecard, descriptive statistics (mean, range) were compiled by rotational land use and soil texture grouping. Data were explored graphically and Pearson correlation coefficients were calculated to measure the strength of the linear relationships between variables.

## 4. Results and discussion

### 4.1. Farmer-research innovation groups

55 expressions of interest to participate in farmer-research innovation groups were received via the AHDB online registration process. The AHDB Knowledge Exchange teams also forwarded some expressions of interest directly. The Organic Research Centre also followed up with existing GREATsoils project groups. Nine project initiation meetings were held regionally. Seven farmer-research innovation groups were identified through this process (Table 1). Project initiation meetings were held with the protected cropping (16/4/2018) and top-fruit sectors (18/4/2018) who had been previously working with the GREATsoils project. These growers are geographically dispersed, and as these systems are very distinct from field-based cropping systems, they felt that aspects of the sampling protocol would not apply, and that existing benchmarking is unlikely to be relevant. Both groups were interested in soil health and its measurement and could see the potential value for their systems arising from improved soil health. However, both groups felt that further testing and development in field-based systems would be valuable before testing / adaptation for their systems. The protected cropping group were particularly interested in integrated molecular testing for soil disease/ health and offered to provide sites for testing of this approach, if it were to reach the stage of farmer-field testing during the SBSH Partnership.

The SBSH Partnership reviewed the location and main farming systems covered by the newly established groups at its meeting in July 2018, together with the remaining expressions of interest. The key gap identified was SW England and dairy systems. As a result of the AHDB Dairy KE programme, Elizabeth Stockdale had an established link with a dairy group in this region. It was therefore agreed to develop this link further to form the locus for the eighth farmer-research innovation group. This was established in autumn 2018.

### 4.2. On-farm soil health assessments

In 2018, the dry summer delayed wetting up in the autumn and hence farmer-research innovation group meetings were moved towards the end of October and into November to ensure good soil conditions for both Visual Evaluation of Soil Structure (VESS) and earthworm counts, i.e., moist warm soils. On-farm meetings with each group took place in October/ November to walk through sampling (at least one site) and discuss each group's sampling approach. A full sampling protocol was developed for the 2018 sampling campaign and then reviewed and updated during the remainder of the SBSH Partnership (2020 sampling protocol provided as Appendix 1). Briefly, sampling sites are 10 m diameter centred on a recorded GPS-location. In each sampling site, usually one per field or field zone, three soil pits (c. spade width x c. 25cm deep) are dug for VESS assessment and earthworm counts, and a representative soil sample is collected for laboratory analysis.

After consultation, the soil sampling guidance provided by the Professional Agricultural Analysis Group (PAAG) which describes the potential interactions which may occur with different cultivation systems (www.nutrientmanagement.org/paag-sampling-guide-routine-samples-oct-2013/) was applied to the collection of soil samples for the Soil Health Scorecard. On arable land, the plough layer is usually 23-28 cm deep but provided the soil in this layer is mixed, a 0-15 cm sample will be representative. However, if the land is min-tilled, applied lime, phosphate and potassium fertiliser will be less fully mixed and may accumulate near the soil surface and a 0-15 cm sample will over-estimate nutrient concentrations to normal plough depth. In this case, samples are better taken to about 23 cm. On grassland, samples to 7.5 cm allow direct comparison of the soil nutrient content with other standard soil tests.

**Table 1** Farmer research-innovation groups established in 2018. 73 farmers plus advisors and observers were actively engaged with the 8 farmer innovation research groups around the UK at the first sampling meetings in autumn 2018. Numbers fluctuated between meetings with c. 100 farm businesses actively engaged during the project.

| Where | No of farmers engaged with the group | Main farming systems | Range of approaches in place |
|---|---|---|---|
| Yorkshire from 21/3/2018 | 18 - 25 | Arable – mixed, with root crops. | *Regular soil testing, linking yield maps and soil nutrient patterns, application of a range of OM sources (FYM, digestate, composts), application of molasses, compost teas; cover crops, companion cropping.* |
| East Anglia from 12/4/2018 | 8 - 12 | Arable – sugar beet – field vegetables | *Extended rotations, integrating grass (for seed), no till, controlled traffic harvest, some OM additions/ cover cropping. Some very sandy soils.* |
| Leics/ Peterborough from 13/4/2018 | 10 - 14 | Arable – mixed | *Paired farmers adopting no till and maintaining effective ploughed systems, agroforestry, targeting organic matter additions, CTF systems. Some very heavy soils.* |
| North East from 25/4/2018 | 4 - 9 | Arable – mixed | *Extended rotations, no till, controlled traffic systems, multi-species cover crops, livestock introduced to arable systems.* |
| Shropshire from 15/5/2018 | 7 - 10 | Lowland livestock (sheep/cattle), arable, field veg. | *Very diverse range of systems within the group but farmers keen to keep this diversity rather than become sector focused. Slurry-based livestock systems (slurry inoculation); intensive and organic veg systems in parallel.* |
| Cumbria from 25/5/2018 | 12 - 14 | Grazing systems; sheep/cattle. | *Existing grazing group – sheep/cattle and mixed grazing systems. Range of grazing management systems in place. Upland fringe.* |
| Inverurie from 31/7/2018 | 7 - 10 | Arable, with some veg (carrots), mixed | *Application of FYM and more recent introduction of compost, extended rotations.* |
| Berks/Wiltshire from 18/10/2018 | 15 - 18 | Dairy, with some combinable cropping | *Reseeding with high sugar grasses, integration of legumes, some maize crops.* |

In autumn 2018, 71 sampling sites were agreed with the farmer-research innovation groups. 63 soil samples were submitted for analysis (89%; Figure 1); 30 of these samples also successfully returned full field records (48%) either via the MySoilSample app (subsequently known as IRecord Soil, under testing with UKCEH), or as paper records. Farmers also agreed to share farm records, including rotational yield data with the project; records were kept in a variety of formats including paper notes, and with a range of levels of detail within farm management software There were also many farms where yields were not recorded by field; sometimes records were by block or by variety (total farm yield) rather than by field.

The scorecard approach developed within Project 2 of the SBSH partnership brings together information about soil chemical, physical and biological properties using "traffic light" coding to identify the properties where there may be a potential risk to crop productivity and/or risk of off-site environmental impact (high soil P levels) and to highlight areas where further investigation is needed to identify appropriate management interventions. Robust evaluation frameworks are already in place for properties such as soil nutrients and pH (The Nutrient Management Guide - RB209 and SAC Technical notes) as well as VESS scores (SRUC and AHDB Healthy Grassland Soils guidance). The Project 2 report also presents potential benchmarks for soil organic matter content, earthworm numbers, bulk density, penetration resistance, microbial biomass carbon and an approach for evaluating nematode community structure. Project 11 of the SBSH partnership evaluated two alternative methods of measuring microbial activity (potentially mineralisable N – PMN and $CO_2$-C burst), providing UK-relevant benchmarks for these two soil assessments, coded using similar 'traffic lights'. The results reported in the sections below are presented using the traffic light benchmarks reported in Project 2 and Project 11 of the SBSH Partnership, and finalised within the SBSH 'Benchmarking tables' (see Section 4.4) where:

Investigate

Review

Continue rotational monitoring (Monitor)

In 2019, the farmer-research innovation groups, continued to test the sampling and recording approach and added a further laboratory measurement (PMN) as a promising indicator of soil microbial activity to the on-farm scorecard. By autumn 2019, most groups had established a link with a member of an appropriate sector AHDB KE team; groups with only a few members successfully recruited more members through the AHDB KE contact and other partners as appropriate.

| | Site characteristics | | | Physical | Chemical | | | | Biological | | Other | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site code | Rainfall region | Rotational cropping | Soil texture class | VESS | pH | P | K | Mg | Earthworms | OM | Ca | Na |
| SBSH18-01 | Low rainfall | Cropping - rotation including late harvested crops | Medium | 2 | 7.9 | 22.8 | 174 | 213 | 0 | 3.7 | 2407 | 29 |
| SBSH18-02 | Low rainfall | Cropping - rotation including late harvested crops | Medium | | 8.1 | 24.4 | 235 | 153 | | 3.2 | 2115 | 24.7 |
| SBSH18-03 | Low rainfall | Cropping - rotation including late harvested crops | Medium | | 8.1 | 7.6 | 143 | 107 | | 3.3 | 2508 | 23.6 |
| SBSH18-04 | Low rainfall | Cropping - rotation including late harvested crops | Medium | | 8.2 | 7.4 | 224 | 156 | | 3.8 | 2599 | 30.2 |
| SBSH18-05 | Low rainfall | Cropping - rotation including late harvested crops | Medium | | 7.7 | 18.6 | 99 | 63 | | 3 | 1885 | 41 |
| SBSH18-06 | Low rainfall | Cropping - rotation including late harvested crops | Medium | | 6.9 | 47.6 | 202 | 75 | | | | |
| SBSH18-07 | Low rainfall | Cropping - rotation including late harvested crops | Medium | | 7.1 | 25.2 | 187 | 66 | | | | |
| SBSH18-08 | Low rainfall | Cropping - rotation including late harvested crops | Medium | | 7.3 | 20.2 | 150 | 61 | | | | |
| SBSH18-09 | Mid rainfall | Grassland - intensively managed | Medium | | 6.5 | 104 | 559 | 273 | | 11.1 | 1447 | 44.4 |
| SBSH18-10 | Mid rainfall | Cropping - rotation including leys | Medium | | 8 | 27 | 125 | 60 | | 4.2 | 2444 | 15.8 |
| SBSH18-11 | Mid rainfall | Grassland - permanent pasture | Heavy | | 6.7 | 31.6 | 337 | 432 | | 12 | 4789 | 50.9 |
| SBSH18-12 | Mid rainfall | Cropping - combinable crops | Heavy | 3 | 7.3 | 39.2 | 398 | 335 | | 11.5 | 6291 | 83.1 |
| SBSH18-13 | Mid rainfall | Cropping - rotation including leys | Medium | | 8.2 | 11 | 136 | 65 | | 4.7 | 2195 | 25.5 |
| SBSH18-14 | Mid rainfall | Not known | Medium | | 7.9 | 17.6 | 178 | 79 | | 6.7 | 2870 | 43 |
| SBSH18-15 | Mid rainfall | Not known | Medium | | 7.2 | 29.8 | 251 | 147 | | 8.5 | 2350 | 59.5 |
| SBSH18-16 | High rainfall | Cropping - rotation including leys | Light | | 6.6 | 27 | 61 | 77 | | 3.4 | 1101 | 28.3 |
| SBSH18-17 | High rainfall | Cropping - rotation including late harvested crops | Light | | 6.5 | 51 | 109 | 47 | | 2.3 | 736 | 20 |
| SBSH18-18 | High rainfall | Grassland - intensively managed | Light | | 7 | 12.8 | 61 | 90 | | 2.7 | 956 | 28.3 |
| SBSH18-19 | High rainfall | Cropping - rotation including leys | Light | | 6.6 | 21 | 199 | 110 | | 3 | 896 | 21.3 |
| SBSH18-20 | High rainfall | Cropping - rotation including late harvested crops | Light | | 7 | 23.2 | 235 | 66 | | 3.6 | 993 | 21 |
| SBSH18-21 | High rainfall | Grassland - intensively managed | Light | | 6.3 | 23.8 | 131 | 51 | | 2.7 | 879 | 17.1 |
| SBSH18-22 | High rainfall | Grassland - permanent pasture | Medium | | 5.8 | 91 | 188 | 83 | | 8.2 | 650 | 20.1 |
| SBSH18-23 | High rainfall | Cropping - rotation including leys | Medium | | 6.6 | 36.6 | 164 | 103 | | 5.6 | 620 | 17.5 |
| SBSH18-24 | High rainfall | Cropping - rotation including leys | Medium | | 6.5 | 40.4 | 114 | 227 | | 7.2 | 1084 | 23.1 |
| SBSH18-25 | High rainfall | Grassland - permanent pasture | Medium | | 6.9 | 63.4 | 197 | 193 | | 22.8 | 1996 | 31.1 |
| SBSH18-26 | High rainfall | Cropping - combinable crops | Medium | 1 | 5.7 | 44.4 | 103 | 83 | 9 | 8.7 | 1159 | 36.8 |
| SBSH18-27 | High rainfall | Cropping - combinable crops | Medium | 2 | 6.4 | 36.2 | 127 | 123 | 18 | 10.2 | 1166 | 34.6 |
| SBSH18-28 | High rainfall | Cropping - combinable crops | Medium | 3 | 6.6 | 33.2 | 114 | 165 | 5 | 6.8 | 1295 | 35.9 |
| SBSH18-29 | High rainfall | Cropping - combinable crops | Medium | 3 | 6.2 | 47.4 | 154 | 75 | 5 | 5.7 | 1291 | 28.6 |
| SBSH18-30 | High rainfall | Cropping - combinable crops | Medium | 3 | 6.7 | 51 | 607 | 281 | 15 | 6.1 | 2123 | 35.8 |
| SBSH18-31 | High rainfall | Cropping - combinable crops | Medium | 2 | 6.5 | 69.4 | 533 | 150 | 19 | 9.7 | 1178 | 32.5 |
| SBSH18-32 | High rainfall | Grassland - permanent pasture | Medium | 3 | 5.8 | 6.8 | 218 | 84 | 0 | 12.8 | 758 | 32.9 |
| SBSH18-33 | High rainfall | Grassland - permanent pasture | Medium | 5 | 5.8 | 4.8 | 129 | 275 | 1 | 33.1 | 2481 | 54.1 |
| SBSH18-34 | High rainfall | Grassland - permanent pasture | Medium | 2 | 5.8 | 10.2 | 69 | 55 | 16 | 4.4 | 773 | 23.6 |
| SBSH18-35 | High rainfall | Grassland - permanent pasture | Medium | 3 | 5.7 | 12.8 | 62 | 54 | 26 | 5.4 | 531 | 18.2 |
| SBSH18-36 | High rainfall | Grassland - permanent pasture | Medium | 3 | 6 | 13 | 40 | 88 | 5 | 6.9 | 1078 | 13.5 |
| SBSH18-37 | High rainfall | Grassland - permanent pasture | Medium | 3 | 6.2 | 6.8 | 62 | 70 | 19 | 9.1 | 1390 | 20.1 |
| SBSH18-38 | Mid rainfall | Cropping - combinable crops | Heavy | 3 | 6.3 | 36 | 259 | 203 | 13 | 7.4 | 2024 | 19.6 |
| SBSH18-39 | Mid rainfall | Cropping - combinable crops | Light | 2 | 6.3 | 50.2 | 243 | 72 | 20 | 6.7 | 1649 | 12.9 |
| SBSH18-40 | Mid rainfall | Cropping - combinable crops | Medium | | 6.7 | 19.2 | 218 | 150 | | 4.7 | 1494 | 15.2 |
| SBSH18-41 | Mid rainfall | Cropping - combinable crops | Medium | | 6.7 | 15.6 | 111 | 143 | | 4.5 | 1541 | 12.8 |
| SBSH18-42 | Mid rainfall | Cropping - combinable crops | Medium | | 5.1 | 17.4 | 180 | 66 | | 5.8 | 965 | 14.8 |
| SBSH18-43 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 7.3 | 27.4 | 274 | 107 | 7 | 5.5 | 1029 | 11.4 |
| SBSH18-44 | Mid rainfall | Cropping - combinable crops | Heavy | 3 | 7.5 | 24.2 | 113 | 150 | 10 | 10.8 | 5302 | 29.3 |
| SBSH18-45 | Mid rainfall | Cropping - combinable crops | Medium | 4 | 7.8 | 37.2 | 352 | 106 | 39 | 5.2 | 2737 | 14.3 |
| SBSH18-46 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 7.2 | 14 | 106 | 105 | 5 | 4.5 | 2503 | 17.5 |
| SBSH18-47 | Mid rainfall | Cropping - rotation including leys | Heavy | 2 | 6.9 | 17.2 | 209 | 113 | 16 | 4.7 | 1797 | 14.9 |
| SBSH18-48 | Mid rainfall | Cropping - rotation including leys | Medium | | 6.9 | 23.6 | 107 | 153 | | 4.9 | 1640 | 25.1 |
| SBSH18-49 | Mid rainfall | Cropping - rotation including leys | Heavy | | 6.8 | 14.4 | 102 | 126 | | 5.6 | 2163 | 25.6 |
| SBSH18-50 | Mid rainfall | Cropping - rotation including leys | Medium | | 6.6 | 47 | 126 | 106 | | 4.2 | 1825 | 26.8 |
| SBSH18-51 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 6.7 | 14.4 | 106 | 81 | 13 | 7.5 | 3085 | 21.5 |
| SBSH18-52 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 7.2 | 24.4 | 146 | 85 | | 7.4 | 4370 | 26 |
| SBSH18-53 | Mid rainfall | Cropping - combinable crops | Heavy | 2 | 7.1 | 29.4 | 219 | 171 | | 6.7 | 3245 | 21 |
| SBSH18-54 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 7.2 | 6.8 | 209 | 50 | 13 | 6.1 | 2469 | 9.8 |
| SBSH18-55 | Mid rainfall | Cropping - combinable crops | Light | 1 | 7.9 | 7 | 117 | 46 | 6 | 5.2 | 3324 | 13.4 |
| SBSH18-56 | Low rainfall | Cropping - rotation including leys | Heavy | 4 | 8.4 | 10.2 | 184 | 60 | 4 | 5.7 | 3885 | 21 |
| SBSH18-57 | Low rainfall | Cropping - combinable crops | Heavy | 4 | 8.3 | 19.8 | 226 | 62 | 5 | 5.4 | 4730 | 17 |
| SBSH18-58 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.7 | 40.6 | 158 | 82 | 13 | 3.4 | 1482 | 9.6 |
| SBSH18-59 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.4 | 60.6 | 173 | 108 | 10 | 3.3 | 1293 | 12.4 |
| SBSH18-60 | Mid rainfall | Cropping - combinable crops | Medium | 2 | 6.1 | 52 | 104 | 59 | 2 | 2.2 | 835 | 9 |
| SBSH18-61 | Mid rainfall | Cropping - rotation including leys | Light | 2 | 6.9 | 59.6 | 106 | 89 | 8 | 2 | 1010 | 16.6 |
| SBSH18-62 | Mid rainfall | Cropping - rotation including leys | Medium | 3 | 6.5 | 17 | 261 | 73 | 4 | 9.6 | 1094 | 19.6 |
| SBSH18-63 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 7 | 37.2 | 148 | 144 | 1 | 2.2 | 816 | 11.8 |

**Figure 1** On-farm Soil Health scorecards collected in 2018 by farmer-research innovation groups. Field vegetables and rotations with late-harvested crops were recorded separately in the field but were grouped together for analysis. For full detail, see Annex 1 – Spreadsheet.

The autumn 2019 sampling campaign began with meetings of the farmer innovation research groups from early October – early November 2019; these were on farm visits which included a visit to review soil health practices at one of the participating farmers and a demonstration of the on-farm sampling protocol as a reminder.  Farmers agreed that paper records were currently more practical for in-field record keeping (site characteristics, VESS, earthworms) and submitted these as photos or scanned documents to the SBSH Partnership team, together with photos of the VESS blocks in many cases.

**Figure 2** Visual Evaluation of Soil Structure, farmer-photographed block. Medium texture, cropping-rotation including late-harvested crops. Most limiting layer score 3. Accompanying notes describe a crumbly structure for 10-15cm over larger angular blocks.

In total, 56 soil health assessments (usually as paired on-farm comparisons) were made by the SBSH farmer-research innovation groups on 20 farms (Figure 3) between early October and mid-December with some limitations to sampling caused by the wet autumn; this was 75% of the samples identified and promised by the farmers. Where the expected samples were not taken, it was usually saturated soil conditions that limited access for sampling. With the move to paper records, a higher proportion of the samples (86%) were submitted with complete information.

| | Site characteristics | | | Physical | Chemical | | | | Biological | | | Other | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site code | Rainfall region | Rotational cropping | Soil texture class | VESS | pH | P | K | Mg | Earthworms | OM | PMN | Ca | Na |
| SBSH19-01 | Scotland - mid | Cropping - rotation including late harvested crops | Light | | 6.2 | 43.2 | 130 | 74 | | 5.1 | 27.15 | 1090 | 21.6 |
| SBSH19-02 | Scotland - mid | Cropping - rotation including late harvested crops | Light | | 6.4 | 32.8 | 113 | 55 | | 5 | 35.66 | 1158 | 18 |
| SBSH19-03 | Scotland - mid | Cropping - combinable crops | Medium | | 6.5 | 47 | 129 | 42 | | 5.4 | 40.04 | 1200 | 25.8 |
| SBSH19-04 | Scotland - mid | Cropping - combinable crops | Medium | | 6 | 23.6 | 66 | 135 | | 5.9 | 65.06 | 1092 | 31.5 |
| SBSH19-05 | Scotland - mid | Cropping - combinable crops | Medium | | 6.6 | 51.2 | 162 | 94 | | 7.6 | 35.12 | 1586 | 27.2 |
| SBSH19-06 | Scotland - mid | Cropping - combinable crops | Medium | | 6.4 | 33 | 158 | 174 | | 4.5 | 30.22 | 1531 | 37.9 |
| SBSH19-07 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 7.3 | 25 | 137 | 137 | 16 | 6.8 | 113.71 | 1900 | 21.8 |
| SBSH19-08 | Mid rainfall | Cropping - combinable crops | Medium | | 7.5 | 11.8 | 93 | 248 | | 6.1 | 37.06 | 1830 | 12.5 |
| SBSH19-09 | Mid rainfall | Cropping - combinable crops | Medium | | 7.6 | 12 | 127 | 302 | | 5.8 | 35.7 | 1870 | 13.5 |
| SBSH19-10 | Mid rainfall | Cropping - combinable crops | Medium | 2 | 6.7 | 22.6 | 235 | 179 | 6 | 6.8 | 43.75 | 1325 | 30.1 |
| SBSH19-11 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 6.6 | 15 | 125 | 168 | 10 | 5.9 | 54.54 | 1155 | 20.5 |
| SBSH19-12 | Mid rainfall | Cropping - combinable crops | Medium | 2 | 6.8 | 10.8 | 110 | 253 | 25 | 5.6 | 80.68 | 1250 | 17.5 |
| SBSH19-13 | Mid rainfall | Grassland - permanent pasture | Medium | 2 | 6.3 | 7 | 315 | 234 | 12 | 15.5 | 197.4 | 4064 | 39.6 |
| SBSH19-14 | Mid rainfall | Cropping - rotation including leys | Medium | 3 | 6.5 | 6 | 359 | 290 | 29 | 12.9 | 165.8 | 4530 | 46.5 |
| SBSH19-19 | High rainfall | Grassland - intensively managed | Medium | 2 | 6.8 | 12.2 | 116 | 124 | 49 | 6.3 | 75.8 | 1240 | 23.5 |
| SBSH19-20 | High rainfall | Grassland - intensively managed | Medium | 2 | 5.9 | 19 | 146 | 138 | 30 | 9.8 | 78.5 | 855 | 20.5 |
| SBSH19-23 | High rainfall | Cropping - rotation including leys | Medium | 2 | 6.6 | 21 | 125 | 149 | 13 | 4.1 | 65.7 | 1185 | 7 |
| SBSH19-24 | High rainfall | Cropping - rotation including leys | Heavy | 1 | 6.4 | 23 | 174 | 82 | 16 | 3.3 | 41.6 | 1190 | 9 |
| SBSH19-25 | High rainfall | Grassland - permanent pasture | Light | 2 | 5.9 | 9.8 | 125 | 54 | 38 | 6.8 | 118.0 | 905 | 15 |
| SBSH19-26 | High rainfall | Grassland - permanent pasture | Light | 2 | 6.3 | 7.2 | 102 | 71 | 52 | 5.5 | 59.2 | 1035 | 17 |
| SBSH19-27 | High rainfall | Grassland - permanent pasture | Light | 2 | 6.5 | 5 | 50 | 158 | 12 | 7.3 | 61.2 | 855 | 10.5 |
| SBSH19-28 | High rainfall | Grassland - permanent pasture | Medium | 2 | 6 | 3.6 | 27 | 28 | 8 | 8.3 | 54.9 | 756 | 9 |
| SBSH19-29 | High rainfall | Grassland - permanent pasture | Medium | 2 | 5.2 | 5 | 59 | 46 | 6 | 14.9 | 138.6 | 410 | 20.5 |
| SBSH19-30 | High rainfall | Grassland - permanent pasture | Medium | 4 | 5.8 | 10.2 | 44 | 34 | 5 | 11.3 | 119.5 | 725 | 5.5 |
| SBSH19-31 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 8.4 | 42 | 189 | 63 | 3 | 4.9 | 59.1 | 2465 | 35.5 |
| SBSH19-32 | Mid rainfall | Cropping - rotation including leys | Light | 1 | 8 | 53 | 129 | 42 | 2 | 3.9 | 83.8 | 1795 | 19.5 |
| SBSH19-33 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 7.7 | 64 | 265 | 82 | 0 | 2.7 | 34.5 | 1275 | 8.5 |
| SBSH19-34 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.7 | 67 | 319 | 64 | 0 | 2.8 | 22.7 | 980 | 7.5 |
| SBSH19-35 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.9 | 60.4 | 303 | 67 | 1 | 3.1 | 39.2 | 845 | 17.5 |
| SBSH19-36 | Mid rainfall | Cropping - combinable crops | Medium | 2 | 8.6 | 18.4 | 106 | 30 | 7 | 3.1 | 69.2 | 2158 | 10.7 |
| SBSH19-37 | Mid rainfall | Cropping - combinable crops | Medium | 3 | 8.5 | 11.6 | 106 | 28 | 1 | 3.2 | 50.0 | 1996 | 10.3 |
| SBSH19-38 | Mid rainfall | Cropping - combinable crops | Light | 2 | 6.8 | 39.2 | 145 | 76 | 5 | 4.4 | 41.7 | 1185 | 11.5 |
| SBSH19-39 | Mid rainfall | Cropping - combinable crops | Light | 2 | 6.6 | 27.8 | 117 | 52 | 0 | 3.7 | 18.2 | 910 | 5.5 |
| SBSH19-40 | Mid rainfall | Cropping - rotation including leys | Medium | 2 | 7.1 | 12.6 | 108 | 107 | 8 | 8.6 | 43.9 | 2785 | 9 |
| SBSH19-41 | Mid rainfall | Cropping - rotation including leys | Heavy | 3 | 7.1 | 18.6 | 195 | 135 | 4 | 8.1 | 91.1 | 3175 | 12 |
| SBSH19-42 | Mid rainfall | Cropping - rotation including leys | Heavy | 4 | 7 | 38.8 | 148 | 124 | 7 | 8.9 | 90.3 | 2780 | 14 |
| SBSH19-43 | Mid rainfall | Cropping - rotation including leys | Heavy | 5 | 7.2 | 49.2 | 232 | 128 | 10 | 8.2 | 65.0 | 2905 | 15 |
| SBSH19-50 | Low rainfall | Cropping - combinable crops | Medium | 2 | 7.7 | 13.6 | 144 | 60 | 18 | 4.6 | 68.3 | 2544 | 47.5 |
| SBSH19-51 | Low rainfall | Cropping - combinable crops | Medium | 2 | 7.9 | 27 | 189 | 40 | 10 | 3.6 | 38.1 | 1987 | 25.2 |
| SBSH19-52 | Low rainfall | Cropping - combinable crops | Medium | 2 | 7.9 | 14.8 | 92 | 57 | 6 | 3.6 | 69.4 | 2198 | 20.1 |
| SBSH19-53 | Low rainfall | Cropping - rotation including late harvested crops | Medium | 3 | 8.6 | 46.4 | 351 | 63 | 13 | 3.3 | 46.1 | 1934 | 9.2 |
| SBSH19-54 | Low rainfall | Cropping - rotation including late harvested crops | Medium | 3 | 8.6 | 12.2 | 201 | 48 | 7 | 2.8 | 37.4 | 2010 | 24.4 |
| SBSH19-55 | Low rainfall | Cropping - combinable crops | Heavy | 3 | 7.7 | 16 | 70 | 36 | 4 | 4 | 32.5 | 2161 | 19.4 |
| SBSH19-56 | Low rainfall | Cropping - combinable crops | Heavy | 3 | 7.9 | 13 | 134 | 56 | 4 | 5.2 | 62.0 | 3276 | 45 |

**Figure 3** On-farm Soil Health scorecards collected in 2019 by farmer-research innovation groups. Field vegetables and rotations with late-harvested crops were recorded separately in the field but have been grouped together here for analysis. For full detail, see Annex 1 – Spreadsheet.

The scorecard approach was also used more widely as a KE tool for reporting and supporting discussion of soil health in 2019. The Wallop Brook Farms' cluster in Hampshire worked with Elizabeth Stockdale directly and collected data using the same protocol (25 assessments). In addition, the AHDB Cereals & Oilseeds Monitor Farms used the approach to underpin discussions about soil health and the use of soil-improving measures as part of the Monitor Farm programme - up to 6 assessments per farm were carried out for the AHDB KE teams on 7 Cereals & Oilseeds Monitor Farms. These more detailed assessments also included measurement of the $CO_2$-burst and particle size distribution (by laser). In total, 120 on-farm soil heath assessments were carried out using the on-farm protocol in 2019.

The data collected in 2018 and 2019 were used in a preliminary review of the "traffic lights" used for benchmarking within the Soil Health scorecard. For example, low earthworm numbers were seen more commonly in light (sandy) soils (Figure 3), as also seen in the Research Site at Gleadthorpe (Project 4). This led to a focus on further collection of Soil Health scorecard data in autumn 2020 to further examine whether earthworm benchmarking for sandy soils should be adjusted. On-farm sampling took place in autumn 2020 under COVID-19 restrictions; 11 soil health assessments were collected 1-to-1 by the project team with members of existing farmer groups focussed on grasslands and rotations with late-harvested crops dominantly on light soils (Figure 4). In addition, the Organic Research Centre carried out sampling on 19 sites (in comparator groups) monitored in the Livewheat project (AHDB Cereals & Oilseeds project P1907309 “Farm-based organic wheat variety trials network”). ADAS also re-sampled the long-term CTF fields at Barfoots (originally sampled as part of the AHDB PF Hort project CP107c “The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems”).

| | Site characteristics | | | Physical | Chemical | | | | Biological | | | Other | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site code | Rainfall region | Rotational cropping | Soil texture class | VESS | pH | P | K | Mg | Earthworms | OM | PMN | Ca | Na |
| SBSH20-01 | Mid rainfall | Grassland - permanent pasture | Medium | 3 | 6.3 | 20.8 | 203 | 338 | 9 | 7.1 | 147 | 1583 | 46.4 |
| SBSH20-02 | Mid rainfall | Grassland - permanent pasture | Medium | 2 | 6.6 | 26.6 | 292 | 242 | 8 | 8.1 | 106 | 1548 | 30.1 |
| SBSH20-03 | Mid rainfall | Grassland - intensively managed | Medium | 3 | 6.1 | 25.2 | 139 | 295 | 13 | 7.3 | 66 | 1599 | 22.2 |
| SBSH20-04 | High rainfall | Grassland - permanent pasture | Light | 2 | 6.1 | 27.8 | 90 | 65 | 22 | 5.3 | 102 | 1420 | 14 |
| SBSH20-05 | High rainfall | Grassland - intensively managed | Light | 2 | 6.3 | 20.8 | 255 | 85 | 16 | 7 | 69 | 1160 | 15 |
| SBSH20-06 | High rainfall | Grassland - intensively managed | Light | 2 | 5.9 | 19.2 | 140 | 50 | 18 | 4.9 | 65 | 895 | 10.5 |
| SBSH20-07 | High rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.6 | 38.2 | 264 | 111 | 8 | 2.5 | 48 | 705 | 5 |
| SBSH20-08 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.4 | 26.6 | 98 | 100 | 4 | 3 | 20 | 805 | 5.5 |
| SBSH20-09 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.8 | 39 | 203 | 113 | 1 | 3 | 30 | 735 | 11 |
| SBSH20-10 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.8 | 46 | 476 | 66 | 8 | 3.5 | 25 | 850 | 27.5 |
| SBSH20-11 | Mid rainfall | Cropping - rotation including late harvested crops | Light | 2 | 6.7 | 48.4 | 452 | 87 | 4 | 3.2 | 26 | 875 | 21 |

**Figure 4** On-farm Soil Health scorecards collected in 2020 by the project team with members of existing farmer groups. For full detail, see Annex 1 – Spreadsheet.

Use of the Soil Health scorecard with the AHDB Cereals & Oilseed Monitor Farms was rolled out further in 2020, and there was also a pilot for AHDB Beef & Lamb Monitor Farms together with ongoing sampling by the Farmer Facilitation Groups working with the Partnership. This added a further 85 Soil Health scorecards to the database in 2020. A small number of sites sampled in 2018 at the beginning of a management change process were targeted for re-sampling in autumn 2021 to investigate the impacts of management change (section 4.4).

In spring 2020, top fruit growers met to discuss soil health for orchards and to review the options for sampling in perennial row crops. For orchards, a Soil Health scorecard pilot was carried out using sampling sites of 10 m length centred on a GPS-location in the alley together with an equivalent row site in both adjacent tree rows. In each sampling site, three soil pits (c. spade width x c. 25cm deep) were dug for VESS assessment and earthworm counts, and soil samples were collected for laboratory analysis from both alley and row (Figure 5). Growers used this adapted protocol in spring or autumn 2020 to collect 48 Soil Health scorecards (each with a separate alley and row scorecard) in apple, cherry and plum orchards; these orchard data are not part of the main database and have been reviewed separately.

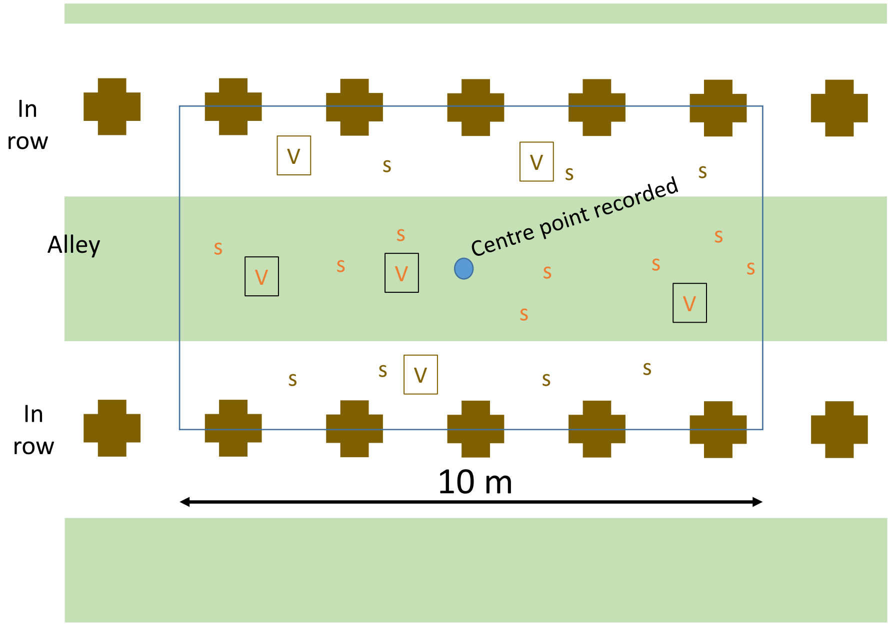



**Figure 5** Sampling design co-developed by the SBSH Partnership and the Sainsburys Grower Interaction Group for top fruit (apples, plums, cherries). V = VESS and earthworm counts. S = soil samples collected for laboratory analyses

As part of, or working with, the SBSH Partnership, 295 Soil Health scorecards (287 with complete data) were collected on farm between 2018 and 2020 across a range of farm system and soil types (Table 2), together with 22 sites in orchards (with separate Soil Health scorecards for row and alley).

**Table 2** Number of sites with Soil Health scorecards showing distribution by rotational cropping system and soil texture group (using the cross-compliance groupings)

| | **Cropping** | | | **Grassland** | **Top fruit** |
|---|---|---|---|---|---|
| **Topsoil texture group** | Rotations with late harvested crops/ field vegetables | Combinable crops | Rotations with leys | | |
| Heavy | 1 | 51 | 21 | 12 | - |
| Medium | 10 | 79 | 34 | 23 | 3 |
| Light | 23 | 24 | 7 | 10 | 19 |

## 4.3. Evaluation of the Soil Health scorecard approach - sampling

The aim of the work within the SBSH partnership was to develop and test a toolkit for soil health monitoring which allows land users in the UK to take site-specific soil health into account when planning and managing resilient and sustainable crop and grassland production for the long term. Project 8 clearly confirmed that there was a desire for farmer-friendly in-field tools to monitor soil health, alongside the submission of soil samples for laboratory analysis. Project 9 confirmed this interest through the active engagement of farmers through the farmer-research innovation groups. The Soil Health scorecard developed by the SBSH Partnership therefore includes in-field assessment of soil structure (VESS) and earthworm counts alongside laboratory analysis of a soil sample. During the group initiation meetings, farmers identified a range of distinct purposes that are supported by soil observations and sampling e.g., checking the performance of fertilisation/liming strategies, planning new fertiliser applications, determination of timeliness for cultivations. The SBSH Partnership recognised that approaches to monitor soil health should therefore fit within those approaches but not necessarily replace them all; on any farm, there are likely to be further but complementary approaches to soil characterisation e.g., zonal sampling of soil P/K for precision fertiliser management.

Simultaneous sampling for all the scorecard measures is essential to make the Soil Health scorecard practicable but requires compromise in the science as most of the measures show some temporal variation. The physical and biological measures require sampling while the soil is both warm and moist, hence suggesting a mid-late spring or early-mid autumn timing, depending on the weather. The date of sampling is less important than the fact that the soil is both moist and warm. Farmer workload is high in both seasons and there is no obvious lull into which such sampling would fit. The initial suggestion of the SBSH Partnership was an autumn sampling timing (as the soil wets up) for the Soil Health scorecard assessment, which would be deployed rotationally (c. once in 3-5 years). Project 8 raised significant concerns about the workload implications of autumn sampling (and hence the likelihood of adoption) and also the difficulty of ensuring a common state for ground cover at sampling sites (crop, stubble, cultivated soil). The alternate timing (in spring after cessation of drainage) is no easier for workload and does not give any more commonality in terms of ground cover. Because the assessment of physical condition included in the Soil Health scorecard is the most limiting layer score from VESS rather than bulk density or penetrometer resistance, the measure is more robust across these different ground cover types. The farmer-research innovation groups discussed sampling timings and agreed that the least-worst option with most flexibility for sampling timing fell in:

- mid-late autumn (after harvest), and
- after the topsoil has wetted up in the autumn, and
- ideally at least 1 month after any cultivations / moderate soil disturbance or manure application.

As outlined in Section 4.2, a high proportion of farmers were able to deliver sampling in this sampling window. The sampling and recording approach required for the soil health scorecard is not considered to be onerous and is able to be fitted into the busy autumn work schedule by most farmers in most years. The most common reactions to discussing sampling amongst the farmer groups were: "*if you want to know the answer then you can always find time to fit it in*" and "*there is always a half-day at least when the weather isn't quite fit enough for drilling, when this could be done*". However, this timing may mean that rotational sampling for soil health does not easily fit at all points of the rotation. In some rotations, this may mean sampling in an actively growing cover crop or after drilling of the next main crop.

Given the overall aim, initial stakeholder workshops (Project 8) suggested that sampling for assessment of soil health in cropping systems should take place once per rotation and at the same point in the rotation to maximise comparability between samples so that the farmer/ grower can monitor long-term trends. Growers/ farmers are in the best place to determine the best point in the rotation to integrate soil health sampling to best inform their practice. During Project 9, the farmer groups confirmed that because wheat is often grown as a break crop in horticultural rotations, a 'first' cereal occurs in almost all cropping systems; there is no other rotational niche which occurs so commonly. Therefore, the most comparable point for making the Soil Health scorecard assessment in cropping systems would be following a first cereal crop. There is no similar point of comparison for all grassland systems; time since last cultivation is likely to be a key factor in determining some grassland soil properties.

If sites are to be established on farm with the intention to measure trends in soil health through time, then a more detailed characterisation of the site, including a full soil textural analysis, subsoil description and profile description to allow identification of the most likely soil series is recommended.

### 4.4. Evaluation of the Soil Health scorecard approach – indicators, presentation and benchmarking

Cross-correlation analysis of the indicators within the Soil Health scorecard found very little co-correlation between the indicators when considered across the dataset as a whole. This supports the potential value of each of the measures as an indicator in their own right. Weak correlations were found between available P and available K (r = 0.384), and between available K and available Mg (r = 0.421). As expected, there is a moderate correlation between pH and available Ca ( r = 0.502). For microbial activity indicators, the relationships with SOM were very similar to those found in Project 11. A moderate correlation was found between PMN and SOM (r = 0.603); in contrast there was no correlation of $CO_2$ burst and SOM (r = 0.110).

The approach of presenting information as a Soil Health scorecard rather than as a single value for soil health was supported very strongly (Project 8) and the use of the traffic light approach (together with the measured values) to give a quick overview has also continued to be valued by the farmer groups and has supported interesting discussions about different management systems and their impact on soil health and wider production and environmental outcomes very effectively with the groups by comparing within and across farms.

Soil health monitoring is a developing area with rapid industry roll-out of proposed solutions. Therefore, the SBSH Partnership sought to work widely with its partners and with the wider industry to create co-ordination and discussion amongst the providers and users of the data so that improved understanding rather than confusion resulting from different approaches could be created for farmers and growers. In summer 2020, each of the Soil Health scorecard indicators was reviewed in light of the data collected across the SBSH Partnership (this project 9 database, together with data and insights from Projects 4 and 7) working together with key academics working in soil health, the main soil testing laboratories and current soil health information providers, mainly the large agronomy companies. The following sections outline the discussion and present the final recommended benchmarking tables.

***Site characteristics***

In the soilquality.org.uk project (Sustainable Agriculture Research and Innovation Club; NE/N012860; 2016-2019) a pilot system was established to compare individual soil test results within a robust decision-support framework. In that project, it had been agreed that to support benchmarking of results, any grouping of data should be:

- Simple so that there is limited confusion at the point of data entry about how to allocate a site to any group;
- Meaningful so that comparison of soil data within any group is informative; and,
- Broad so that there are always a good number of datapoints within the group for comparison.

For the Soil Health scorecard, the simple land-use, climate and soil groupings recommended by soilquality.org.uk were tested.

*Climate*

The UK Meteorological Office regions were used to group sites by climate for comparison

- Northern Scotland, Eastern Scotland, Western Scotland,
- North West England, North East England, Midlands, Eastern England, Southern England, South West England,
- Northern Ireland,
- Wales.

Soil Organic Matter is the only measured soil characteristic where climate is used to adjust the benchmarks, where the key climate factor that Verheijen *et al.* (2005) had found to be of importance was rainfall. They used 3 rainfall groups – low (< 650 annual average precipitation mm), mid (650 – 800), high (800 -1100)). These groups were allocated by the Met. Office climate regions. If the framework were to be extended to the uplands, then further wetter (upland) categories would need to be added in some regions. Within the small Soil Health scorecard dataset here, data are presented by rainfall region rather than using the Met. Office climate regions to optimise the size of the groups for comparisons.

*Land use*

Broad land use groupings were used so that there is sufficient breadth of data to compare within the group, and for the group to be further stratified by soil type. NERC land cover mapping only distinguishes managed agricultural land use as Arable & Horticulture or Improved grassland. This would not be sufficient. It was agreed that the following user-selected land use categories would be used to group sites for comparison in both England and Scotland:

- Cropping – combinable crops
- Cropping – rotations including late harvested crops
- Cropping – rotation including leys
- Cropping – field-scale vegetables
- Grassland – intensively managed
- Grassland – permanent pasture

In the future further land use categories could be added e.g. natural ecosystem, perennial crops (non-grass), upland/LFA pasture.

Benchmarking is carried out separately for cropping and grassland systems, for pH, earthworms, soil organic matter and for indicators of microbial activity. Benchmarking is not further stratified according to the land-use categories. However, it was noted that differences in tillage intensity and soil organic matter inputs are likely to be partially clustered according to cropping systems. Within the Soil Health scorecard dataset, the few scorecards for field-scale vegetables (3) were grouped with the rotations including late harvested crops to optimise the size of the groups for comparisons.

*Soil*

While data on soil type is available for England and Wales at 1:250,000 (LandIS) and at smaller scales for Scotland (Scotland's Soils), the natural variation of soil between and within fields means that in-field recording of soil texture into broad "texture class" groups will give the most useful grouping variable for on-farm data. It was agreed that topsoil texture class should be the main factor used for benchmarking and to group data for comparison. There are a range of soil textural classifications that are currently in use:

- The texture triangle developed by the former Soil Survey of England and Wales which gives 11 texture classes for mineral soils. Further sub-divisions are added according to the size of sand grains (coarse, medium, fine), and additional classes are used for naturally calcareous soils with >1% calcium carbonate, organic and peaty soils. Where soils are sent for analysis, a textural analysis report includes the % sand, silt, clay and the texture class according to this triangle.
- Current Defra publications with a focus on erosion risk use a simplified version of the texture triangle with just 3 main groupings (for mineral soils only) - sandy and light silty, medium and heavy. In the Single Payment Scheme cross-compliance guidance for soil management, a further class of peaty soils is added which includes soils where the organic content of the topsoil is more than 20% organic matter
- In the current Nutrient Management Guide (RB209) soil depth is taken into account along with texture – in particular to support decisions about nitrate retention overwinter. This gives seven soil categories (peaty, organic, shallow, light sand, deep silty, medium, deep clayey).

The cross-compliance soil types were used to create soil groups for use in the Soil Health scorecard: light, medium and heavy. Benchmarks in the Soil Health scorecard are currently only applicable for mineral soils i.e., excluding peaty soils. Soil organic matter is the only soil characteristic where the different texture classes are used to set benchmarks. Because of the way the data were collected, there is a cluster of data for shallow calcareous soils (largely Andover series); data for this group is summarised separately when considering soil organic matter.

The properties of subsoils have a marked impact on soil hydrology (e.g. drainage, risk of compaction), other soil characteristics (e.g. nutrient supply, stoniness) and the opportunities for soil management. Hence although characterisation of the subsoil is not required for the Soil Health scorecard *per se*, it would be useful to make in-field observations of sub-soil characteristics; this could be recorded using the same simple classes, plus to identify very shallow soils a further class (i.e. None) would be added.

***Physical***

The Visual Evaluation of Soil Structure method (VESS) has been shown to be strongly related to laboratory measures of soil structure and is recommended as a tool for rapid assessment of soil structural quality allowing targeting of more detailed measures as required (Ball *et al.* 2007). Farmers also valued the photographic records of the soil blocks highly. The VESS data collected within the SBSH Partnership show a range of VESS scores for each soil texture group in cropping and grassland systems (Table 3b), review of these data did not suggest any need to change the benchmarking ranges proposed in Project 2 (Table 3a). It was noted that for light sandy soils that a VESS score of 2 (indicating presence of crumbs and subangular blocks) may in fact be more beneficial than a VESS score of 1, which may indicate some single grain structure. However, this information/ interpretation does not need a change in the benchmarking criteria.

**Table 3** VESS score for most limiting layer (i.e., the highest value observed in a 0-25 cm soil block)

a) Final recommended benchmarking table for use in the Soil Health scorecard for the most limiting layer score (VESS assessment)

| Traffic light | Ranges | |
|---|---|---|
| Monitor | 1 or 2 | CONTINUE ROTATIONAL MONITORING Good soil structure. Friable / crumbly. Small round aggregates. Make a comparison with an area known to be poor (e.g. gateway) and likely to be good (e.g. hedge bottom). Consider including an assessment of subsoil. Assess regularly and especially where it has been necessary to traffic or cultivate the soil in wet conditions. |
| Review | 3 | REVIEW Adequate soil structure. Firm. Larger aggregates, some angular, but most aggregates break down. Make a comparison with an area that is known to be poor (e.g. gateway) and likely to be good (e.g. hedge bottom), include consideration of subsoil. Assess regularly and especially where it has been necessary to traffic or cultivate the soil in wet conditions. |
| Investigate | 4 or 5 | INVESTIGATE Poor soil structure. Compact or very compact with impacts on rooting observed. Serious compaction or runoff must be dealt with quickly. Major compaction problems are more commonly tackled as part of the cultivation operations for the next crop. Check subsoil layers, alleviating compaction in surface layers may be of limited value if subsoil has suffered compaction damage. It is essential that all operations to address poor structure are done under the right soil conditions. Working soil in wet conditions will usually make the problem worse. |

b) Summary of most limiting layer (VESS) data from Soil Health scorecard database collated in Project 9

| | **Cropping** | | **Grassland** | |
|---|---|---|---|---|
| **Texture group** | Range | Average | Range | Average |
| Heavy | *1-5* | *2.27* | *1-3* | *2.42* |
| Medium | *1-4* | *2.40* | *1-5* | *2.37* |
| Light | *1-3* | *2.05* | *2* | 2 |

Examination of the soil surface to identify signs of soil erosion or poaching is part of the initial site evaluation within the VESS methodology (Table 4). This is used to identify the likely variation in soil structural quality across the field, in particular to identify if there is a high proportion of the field where poor soil structure is limiting soil function, and hence to direct further investigation. The Project 14 report summarises current guidance on how to rectify soil structural damage, including the use of vigorous rooting green crops. It also provides signposting for a farmer/grower using the soil health scorecard to the most appropriate options for improving soil physical condition within their sector.

**Table 4** Qualitative surface assessment is used as part of the VESS approach to identify areas within a field where there may be poor soil structure

| Surface condition | Observations characterising each class<br>**Cropping** | <br>**Grassland** |
|---|---|---|
| Good | • Soil surface covered by vegetation and/or residues<br>• No standing water<br>• No deep wheelings | • Sward intact<br>• No poaching<br>• Few wheelings |
| Moderate | • Areas of surface water<br>• Poor vegetation growth or soil surface cover | • Surface poached<br>• Wheelings in places<br>• More weed species |
| Poor | • Surface capping<br>• Poor growth<br>• Deep wheelings present | • Surface capping<br>• Soil exposed<br>• Severe poaching<br>• Poor sward quality |

Assessment of bulk density requires collection of intact cores, drying and weighing facilities and is not well suited to routine use by farmers or their advisors on-farm. This measure may be useful as part of a more detailed sampling campaign and is required, together with stoniness, if any measure is to be expressed as a stock (i.e., t/ha) basis. Penetration resistance data collected within Project 4 showed that the values obtained were highly dependent on soil water content at the time of sampling. Hence this measure was not considered to be robust enough for comparison and benchmarking between sites or seasons. However, the use of a penetrometer on farm can help with rapid scouting of soil compaction issues in the field; the focus in such circumstances is on detecting differences in resistance to penetration within the profile to detect compaction (especially the low-high-low patterns with depth) rather than absolute values. Penetrometers can be purchased; many farmers make their own from steel rod with a handle welded at the top. The consultation agreed that these measures should not be added to the routine Soil Health scorecard.

The development of structure in subsoil is driven dominantly by physical processes and is mainly determined by the inherent characteristics of any soil, especially texture and stoniness. However agricultural management can transform the structure of the sub-soil e.g. through deep tillage and compaction. Poor topsoil structure is often linked to poor subsoil structure (Ball *et al.* 2015) and hence further evaluation of sites with poor surface condition (Review or Investigate groupings) should include an assessment of subsoil, together with a comparison with an adjacent unmanaged area to distinguish natural consolidation from processes resulting from land use practice. Ball *et al.* (2015) describe a method to assess subsoil structure numerically (subVESS). For this assessment, a mechanical digger is needed to dig a trench > 60 cm wide, 1 m deep (where underlying parent permits) and not less than 2 m in length. The final flowchart for subVESS is available at:
https://www.sciencedirect.com/science/article/pii/S0167198715001506

Some farmers and advisors are also using in-field assessment of infiltration rates and aggregate stability; these can give good site comparisons when conducted on the same day for example to support a field demonstration day but are not robust enough for widespread comparison and benchmarking between sites or between seasons. Simple farmer accessible methods are reported by the USA Natural Resource Conservation Service:
(e.g., www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167178.pdf;
www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053268.pdf).
The consultation agreed that these measures should not be added to the routine Soil Health scorecard.

***Chemical***

Groupings and traffic lights used within the Soil Health scorecard were set in Project 2 with reference to the categories used by PAAG and production-based information – Nutrient Management Guide RB209 and Scotland's Farm Advisory Service (FAS) Technical Notes TN714 and TN656. The Soil Health Scorecards reported here were dominantly sampled in England with a few samples collected in Scotland (10) and Wales (2). Therefore, for ease of collation, the extraction methods reported are the England and Wales methods and these are expressed in relation to the Index system presented within the Nutrient Management Guide. For application in practice, separate benchmarking based on the extractants used for agronomic testing in Scotland and the FAS Technical Notes has been developed in parallel (Tables 8 and 10).

*pH*

The pH data collected within the SBSH Partnership show a range of pH values for each soil texture group in cropping (Table 5b) and grassland systems (Table 6b), review of these data did not suggest any need to change the benchmarking ranges proposed in Project 2 (Table 5a, Table 6a).

**Table 5** pH measured using the standard 1:5 ratio of soil/water – cropping

a) Final recommended benchmarking table for use in the Soil Health scorecard for pH in cropping

| Traffic light | Ranges | |
|---|---|---|
| Investigate | ≤ 5.49 | INVESTIGATE Potential problems with aluminum toxicity<br>Liming is usually required every 3-5 years to maintain pH, it will need to be done more frequently on lighter land. Where large changes in pH are required, a long-term liming programme may be needed. |
| Review | 5.5-6.49 | REVIEW Ensure there is a robust liming plan in place on non-calcareous soils to maintain pH |
| Monitor | 6.5-7.49 | CONTINUE ROTATIONAL MONITORING On non-calcareous soils, ensure that the lime rates used in the liming plan are not over-correcting. It may be better to use lower rates more often and maintain pH at 7 unless if there are very sensitive crops (such as oilseed rape, sugar beet, peas) in the rotation. |
| Review | ≥ 7.5 | REVIEW Potential nutrient interaction issues<br>Monitor crops for trace element deficiencies; foliar feeds will be more effective than soil applications in high pH soils |

b) Summary of pH data for cropping from Soil Health scorecard database collated in Project 9

| | | |
|---|---|---|
| **Texture group** | Range | Average |
| Heavy | *6.0 - 8.7* | *7.60* |
| Medium | *5.1 - 8.6* | *7.16* |
| Light | *5.7 – 8.4* | *6.88* |

**Table 6** pH measured using the standard 1:5 ratio of soil/water – grassland

a) Final recommended benchmarking table for use in the Soil Health scorecard for pH in grassland

| Traffic light | Ranges | |
|---|---|---|
| Investigate | ≤ 5.49 | INVESTIGATE Where biodiverse acid grasslands are not the management aim, liming is usually required every 3-5 years to maintain pH, it will need to be done more frequently on lighter land. Where large changes in pH are required, a long-term liming programme may be needed. |
| Review | 5.5-5.99 | REVIEW Ensure that there is a robust liming plan in place on non-calcareous soils to maintain pH |
| Monitor | 6.0-6.49 | Liming may be needed for reseeds<br><br>CONTINUE ROTATIONAL MONITORING |
| | 6.5–7.49 | Ensure that there is a robust liming plan in place on non-calcareous soils to maintain pH |
| Review | ≥ 7.5 | REVIEW Potential nutrient interaction issues<br><br>Where high pH soils are used for livestock production, trace mineral deficiencies including cobalt, manganese, zinc and copper are aggravated as a result of the high pH soils. Hay (or silage) may have high Ca content and lower than desirable Mg or K contents and a high calcium to phosphorus ratio of the forage which can have negative impacts on livestock performance. These issues cannot be managed in the soil and should be addressed through careful planned grazing, with dietary supplementation as needed. |

b) Summary of pH data for grassland from Soil Health scorecard database collated in Project 9

| | **Grassland** | |
|---|---|---|
| **Texture group** | Range | Average |
| Heavy | *6.7 - 8.3* | *7.41* |
| Medium | *5.1 – 8.6* | *6.53* |
| Light | *5.9 – 7.0* | *6.32* |

*Extractable P*

Phosphorus (P) losses from croplands are a major driver of eutrophication leading to harmful and nuisance algal blooms in waterbodies. Agronomic sampling/ testing is not a complete predictor of environmental risk, however, as the amount of P measured by agronomic testing increases, P losses have been shown to increase (Osterholz *et al.* 2020). Therefore, there are amber and red traffic lights at high P (environmental risk) as well as at low P (potential constraint to productivity). The extractable P data collected within the SBSH Partnership show a range of values for each soil texture group in cropping and grassland systems (Table 7b), review of these data did not suggest any need to change the benchmarking ranges proposed in Project 2 (Table 7a, Table 8).

*Extractable K*

In contrast to P, there is no recognised environmental risk of high K levels. The benchmarking ranges proposed in Project 2, therefore have a simple ‘more is better’ response linked to the soil indices/status which provide information on the likely response to fresh fertiliser addition (Table 9, 10). While target maintenance indices are different for light soils (i.e., Index 1), this is still a level that is considered a potential risk to production and hence is still presented as amber. Information is given on the impacts of potential imbalances in K:Mg during grazing at Index 3 (H) and higher. The extractable K data collected within the SBSH Partnership show a range of values for each soil texture group in cropping and grassland systems (Table 9b), review of these data did not suggest any need to change the benchmarking ranges proposed in Project 2 (Table 9a, Table 10).

*Extractable Mg*

The benchmarking ranges proposed in Project 2 are linked to the soil indices/status which provide information on the likely response to fresh fertiliser addition (Table 11, 12). Groupings and traffic lights also take account of the impact of very high Mg levels on structural stability especially in silty clay soils where Ca is moderate/low.

The extractable Mg data collected within the SBSH Partnership show a range of values for each soil texture group in cropping and grassland systems (Table 11b), review of these data did not suggest any need to change the benchmarking ranges proposed in Project 2 (Table 11a, Table 12).

**Table 7** Extractable P measured using the Olsen method (England and Wales)

a) Final recommended benchmarking table for use in the Soil Health scorecard for extractable P (Olsen, ppm) as used routinely for both cropping and grassland in England and Wales

| Traffic light | Ranges | |
|---|---|---|
| Investigate | ≤ 9 | INVESTIGATE Index 0. P should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. The best crop response may be seen where P is applied in early spring together with nitrogen. |
| Review | 10-15 | REVIEW Index 1. P should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. The best crop response may be seen where P is applied in early spring together with nitrogen. |
| Monitor | 16-45 | CONTINUE ROTATIONAL MONITORING Index 2 and Index 3. A clear rotational P management plan is needed to maintain the soil reserve without compromising productivity or increasing environmental risk |
| Review | 46-70 | REVIEW Index 4. A clear rotational P management plan is needed to sustainably maintain the soil reserve whilst reducing the environmental risk |
| Investigate | ≥ 71 | INVESTIGATE Above Index 4. Potential risk to the environment. A clear rotational P management plan is needed to sustainably run-down the soil reserve without compromising productivity |

b) Summary of extractable P (Olsen, ppm) data from Soil Health scorecard database collated in Project 9

| | **Cropping** | | **Grassland** | |
|---|---|---|---|---|
| **Texture group** | Range | Average | Range | Average |
| Heavy | *5.6 - 125* | *27.04* | *4.4 - 36* | *16.49* |
| Medium | *4.8 - 112* | *25.05* | *3.6 - 104* | *21.58* |
| Light | *7.0 - 69* | *36.50* | *5.0 - 90* | *24.78* |

**Table 8** Final recommended benchmarking table for use in the Soil Health scorecard for extractable P (Modified Morgans, ppm) as used routinely for both cropping and grassland in Scotland

| Traffic light | Ranges | |
|---|---|---|
| Investigate | 0 - 1.7 | INVESTIGATE Very Low. P should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. The best crop response may be seen where P is applied in early spring together with nitrogen. |
| Review | 1.8 - 4.4 | REVIEW Low. P should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. The best crop response may be seen where P is applied in early spring together with nitrogen. |
| Monitor | 4.5 – 13.4 | CONTINUE ROTATIONAL MONITORING M- to M+. A clear rotational P management plan is needed to maintain the soil reserve without compromising productivity or increasing environmental risk |
| Review | 13.5 - 30.0 | REVIEW High. A clear rotational P management plan is needed to sustainably maintain the soil reserve whilst reducing the environmental risk |
| Investigate | >30 | INVESTIGATE Very High. Potential risk to the environment. A clear rotational P management plan is needed to sustainably run-down the soil reserve without compromising productivity |

**Table 9** Extractable K (ppm) measured using the ammonium nitrate extraction method (England and Wales)

a) Final recommended benchmarking table for use in the Soil Health scorecard for extractable K for both cropping and grassland in England and Wales

| Traffic light | Ranges | |
|---|---|---|
| Investigate | ≤ 60 | INVESTIGATE Index 0. K should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. Care is needed where K fertiliser is applied for grassland to avoid the risks of luxury uptake of K under cutting and inducing hypomagnesaemia (low Mg) under grazing. |
| Review | 61-120 | REVIEW Index 1. K should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. Care is needed where K fertiliser is applied for grassland to avoid the risks of luxury uptake of K under cutting and inducing hypomagnesaemia (low Mg) under grazing. |
| Monitor | 121-240 | CONTINUE ROTATIONAL MONITORING Index 2. A clear rotational K management plan is needed to maintain the soil reserve without compromising productivity. |
| Monitor | ≥ 241 | CONTINUE ROTATIONAL MONITORING Index 3 and higher. A clear rotational K management plan should reduce and sustainably maintain the soil reserve without compromising productivity. Care is particularly needed to maintain Mg where K levels are high to avoid the risks of inducing hypomagnesaemia (low Mg) under grazing. |

b) Summary of extractable K data (ppm) from Soil Health scorecard database collated in Project 9

| | **Cropping** | | **Grassland** | |
|---|---|---|---|---|
| **Texture group** | Range | Average | Range | Average |
| Heavy | *70 - 653* | *209.1* | *60 -337* | *144.9* |
| Medium | *66 - 607* | *185.9* | *27 - 559* | *149.7* |
| Light | *61 - 476* | *171.0* | *50 - 375* | *138.7* |

**Table 10** Final recommended benchmarking table for extractable K (Modified Morgan's extraction, ppm) for use in the Soil Health scorecard for both cropping and grassland in Scotland.

| Traffic light | Ranges | |
|---|---|---|
| Investigate | 0 - 39 | INVESTIGATE Very Low. K should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. Care is needed where K fertiliser is applied for grassland to avoid the risks of luxury uptake of K under cutting and inducing hypomagnesaemia (low Mg) under grazing. |
| Review | 40 - 75 | REVIEW Low. K should be applied in fertiliser / organic materials to help meet crop need and build the soil reserve. Care is needed where K fertiliser is applied for grassland to avoid the risks of luxury uptake of K under cutting and inducing hypomagnesaemia (low Mg) under grazing. |
| Monitor | 76 - 200 | CONTINUE ROTATIONAL MONITORING M- to M+. A clear rotational K management plan is needed to maintain the soil reserve without compromising productivity. |
| Monitor | >200 | CONTINUE ROTATIONAL MONITORING H and higher. A clear rotational K management plan should reduce and sustainably maintain the soil reserve without compromising productivity. Care is particularly needed to maintain Mg where K levels are high to avoid the risks of inducing hypomagnesaemia (low Mg) under grazing. |

**Table 11** Extractable Mg (ppm) measured by ammonium nitrate extraction (England and Wales)

a) Final recommended benchmarking table for use in the Soil Health scorecard for extractable Mg for both cropping and grassland in England and Wales

| Traffic light | Ranges | |
|---|---|---|
| Investigate | ≤ 25 | INVESTIGATE Index 0. Where soil acidity also needs to be corrected, applying magnesian limestone is the best way to maintain soil Mg at a satisfactory level. An application of 5 t/ha of magnesian limestone will add at least 450 kg Mg /ha, and this Mg will become plant-available over many years. Where the Mg status is low but additional lime is not required, a range of alternative sources of Mg are available. Foliar Mg can also be applied where plant deficiency symptoms are seen. |
| Review | 26-50 | REVIEW Index 1. Where soil acidity also needs to be corrected, applying magnesian limestone is the best way to maintain soil Mg at a satisfactory level. An application of 5 t/ha of magnesian limestone will add at least 450 kg Mg /ha, and this Mg will become plant-available over many years. Where the Mg status is low but additional lime is not required, a range of alternative sources of Mg are available. Foliar Mg can also be applied where plant deficiency symptoms are seen. |
| Monitor | 51-350 | CONTINUE ROTATIONAL MONITORING Index 2 – Index 5. A clear rotational Mg management plan will allow the soil reserve to be maintained without compromising productivity. |
| Review | ≥ 351 | REVIEW Above Index 5. High soil Mg concentrations do not damage crop growth directly, but may affect plant availability of other cations such as potassium or calcium.<br>A clear rotational Mg management plan will allow the soil reserve to be reduced, and then maintained without compromising productivity. Careful planned grazing and dietary supplementation may be need in grassland on high Mg soils. If liming is necessary, consider the sources of lime available and, where feasible, select a low Mg lime. High Mg levels may reduce aggregate stability in some clay soils, if Na levels are also high and Ca levels are low. |

b) Summary of extractable Mg data from Soil Health scorecard database collated in Project 9

| | **Cropping** | | **Grassland** | |
|---|---|---|---|---|
| **Texture group** | Range | Average | Range | Average |
| Heavy | *17 - 450* | *105.4* | *33 - 432* | *119.0* |
| Medium | *24 - 895* | *117.6* | *28 - 338* | *121.2* |
| Light | *24 – 580* | *82.3* | *50 - 158* | *76.2* |

**Table 12** Final recommended benchmarking table for use in the Soil Health scorecard for extractable Mg (Modified Morgan's extraction, ppm) for use in the Soil Health scorecard for both cropping and grassland in Scotland.

| Traffic light | Ranges | |
|---|---|---|
| Investigate | 0-19 | INVESTIGATE Very Low. Where soil acidity also needs to be corrected, applying magnesian limestone is the best way to maintain soil Mg at a satisfactory level. An application of 5 t/ha of magnesian limestone will add at least 450 kg Mg /ha, and this Mg will become plant-available over many years. Where the Mg status is low but additional lime is not required, a range of alternative sources of Mg are available. Foliar Mg can also be applied where plant deficiency symptoms are seen. |
| Review | 20-60 | REVIEW Low. Where soil acidity also needs to be corrected, applying magnesian limestone is the best way to maintain soil Mg at a satisfactory level. An application of 5 t/ha of magnesian limestone will add at least 450 kg Mg /ha, and this Mg will become plant-available over many years. Where the Mg status is low but additional lime is not required, a range of alternative sources of Mg are available. Foliar Mg can also be applied where plant deficiency symptoms are seen. |
| Monitor | 61-1000 | CONTINUE ROTATIONAL MONITORING M- to High. A clear rotational Mg management plan will allow the soil reserve to be maintained without compromising productivity. |
| Review | > 1000 | REVIEW Very High. High soil Mg concentrations do not damage crop growth directly, but may affect plant availability of other cations such as potassium or calcium.<br>A clear rotational Mg management plan will allow the soil reserve to be reduced, and then maintained without compromising productivity. Careful planned grazing and dietary supplementation may be need in grassland on high Mg soils. If liming is necessary, consider the sources of lime available and, where feasible, select a low Mg lime. High Mg levels may reduce aggregate stability in some clay soils, if Na levels are also high and Ca levels are low. |

*Other extractable nutrients/micro-nutrients*

Broad spectrum soil analysis is now used more commonly by land managers to measure available soil micronutrients (Na, Ca, S, Mn, Cu, B, Zn, Mo and Fe) and identify whether a micronutrient deficiency could be limiting the achievement of yield potential at any site. The pool sizes of these micronutrients are largely determined by the soil parent material and hence these measurements can be considered as one of the inherent characteristics of the soil, rather than a soil health measurement. No benchmarking for micronutrients was therefore proposed. However, where soil samples are being collected and submitted for analysis as part of a soil health monitoring programme, the additional cost of this extended analysis is relatively small.

Project 9 included measures of both Ca and Na alongside the Soil Health scorecards (Table 13). Earlier data and feedback from farmers /advisors suggested there may be more soils at both the low and high ends of the range than are considered by current guidance. The consultation noted that Na measurement can show high temporal variability between samples collected in the same location and hence did not recommend measurement of Na as part of a soil health monitoring programme. Typically, available Ca falls in the range 1000 - 2500 ppm (mg Ca / kg). Very high levels of available Ca (> 3500 ppm), often associated with high pH, were measured in 7% of Soil Health scorecard samples. Such high levels of Ca do not damage crop growth directly but may affect the plant availability of other cations such as potassium, magnesium. Potentially limiting low levels of Ca (<950 ppm) were found in 10% of Soil Health scorecard samples; these soils were sometimes, but not always, within the Review or Investigate groupings for pH, hence liming materials containing Ca may not be added routinely. Therefore, the consultation agreed that whilst these measures should not be added to the routine Soil Health scorecard, where soil samples are submitted for analysis as part of a soil health monitoring programme, measurement of Ca may be valuable to land managers to help guide the development of a site-specific soil management plan.

**Table 13.** Summary of extractable Ca and Na data from Soil Health scorecard database collated in Project 9

a) Extractable Ca (ppm)

| | Cropping | | Grassland | |
|---|---|---|---|---|
| **Texture group** | Range | Average | Range | Average |
| Heavy | *1005 - 6256* | *2737* | *1280 - 4789* | *2424* |
| Medium | *620 - 4530* | *2007* | *410 - 4064* | *1671* |
| Light | *683 - 3324* | *1368* | *771 - 1420* | *986* |

b) Extractable Na (ppm)

| | Cropping | | Grassland | |
|---|---|---|---|---|
| **Texture group** | Range | Average | Range | Average |
| Heavy | *3.5 - 83.1* | *16.1* | *6.0 - 51.0* | *18.0* |
| Medium | *4.6 - 59.5* | *18.4* | *5.5 - 54.1* | *21.7* |
| Light | *4.0 - 150* | *18.3* | *6.0 - 28.3* | *14.2* |

***Biological***

*Earthworms*

Groupings and traffic lights used within the Soil Health scorecard were initially set in Project 2 by reference to the literature as there were few datasets available for the UK. Stroud (2019) reported a pilot survey using farmer-collected earthworm data (largely from cropping systems) in the UK. Data on earthworm numbers collected in Project 4 and some preliminary observations by the project team suggested that very sandy soils (> 70% sand) may support lower earthworm numbers. However, the data collected during Soil Health scorecard sampling (Tables 14b and 15b) does not support any separation of earthworm benchmarks by soil texture group.

Data on earthworm numbers collected in Projects 4, 7 and 9, as well as during associated knowledge exchange events, have highlighted that observed earthworm numbers vary greatly depending on soil conditions (temperature, moisture) and sampling proximity to tillage and /or manure applications so that very different numbers may be counted in samples repeated only a short time apart. However, Project 9 confirmed that observation and counting earthworms is engaging and immediately accessible to farmers. Where a block of soil is already being collected for VESS, then earthworm numbers are an appropriate additional low-cost biological indicator.

**Table 14** Earthworm numbers counted in a block of soil in the field – cropping

a) Final recommended benchmarking table for use in the Soil Health scorecard for earthworms in cropping systems

| Traffic light | Number per 20x20x20 cm spadeful | |
|---|---|---|
| Investigate | ≤3 | INVESTIGATE Depleted. Crop rotations characterised by high tillage intensity and low inputs of organic matter through roots, residues and organic manures are often associated with low earthworm numbers. Reducing tillage intensity and increasing organic matter inputs wherever possible will benefit soil biology and is likely to be reflected in increased earthworm numbers. |
| Review | 4-8 | REVIEW Intermediate. Deep burrowing earthworms are most strongly affected by tillage practice with low populations in crop rotations with regular ploughing and intensive cultivations for seed-bed preparation e.g. for potatoes. Considering the earthworm species present and the balance between juveniles and adults can be useful to give more information about the factors affecting earthworm populations. |
| Monitor | ≥9 | CONTINUE ROTATIONAL MONITORING Typical. There is no right number. In cropping systems, no or non-inversion tillage coupled with regular inputs of organic matter can lead to large and diverse earthworm populations. Considering the earthworm species present and the balance between juveniles and adults can be useful to give more information about the factors affecting earthworm populations |

b) Summary of earthworm data (number in a 20 x 20 cm spadeful) for cropping systems from Soil Health scorecard database collated in Project 9

| | **Cropping** | |
|---|---|---|
| **Texture group** | Range | Average |
| Heavy | *0 - 21* | *7.8* |
| Medium | *0 - 43* | *11.4* |
| Light | *0 - 35* | *8.0* |

**Table 15** Earthworm numbers counted in a block of soil in the field – grassland

a) Final recommended benchmarking table for use in the Soil Health scorecard for earthworms in grassland systems

| Traffic light | Number per 20x20x20 cm spadeful | |
|---|---|---|
| Investigate | ≤9 or predominantly one species | INVESTIGATE Depleted. Acid wet grasslands, especially those which are waterlogged for a significant part of the year, are often associated with low earthworm numbers. Often the main factors affecting earthworm numbers and diversity need to be addressed through physical (drainage) or chemical (liming) interventions. These changes are also likely to benefit grassland productivity as well as soil biology and are likely to be reflected in increased earthworm numbers. |
| Review | 10-19 | REVIEW Intermediate. High rate applications of slurry or digestate are often associated with the short-term disturbance of earthworm populations. Considering the earthworm species present and the balance between juveniles and adults can be useful to give more information about the factors affecting earthworm populations. |
| Monitor | ≥20 with good range of eco-types | CONTINUE ROTATIONAL MONITORING Typical. There is no right number. In grasslands neutral and moist, but well-aerated, soils with diverse swards are often associated with large and diverse earthworm populations Considering the earthworm species present and the balance between juveniles and adults can be useful to give more information about the factors affecting earthworm populations. |

b) Summary of earthworm data (number in a 20 x 20 cm spadeful) for grassland from Soil Health scorecard database collated in Project 9

| | **Grassland** | |
|---|---|---|
| **Texture group** | Range | Average |
| Heavy | *4 - 24* | *13.3* |
| Medium | *0 - 49* | *12.1* |
| Light | *6 - 52* | *23.9* |

When earthworm number data were collected as part of the Soil Health scorecards, most farmers also recorded the numbers of adults and juveniles, as well as observing differences in earthworm ecotypes (anecic, endogeic, epigeic) using the AHDB resources (https://ahdb.org.uk/knowledge-library/how-to-count-earthworms). However, there are no clear patterns between sites and the consultation confirmed that the Soil Health scorecard measure would remain as the total number of earthworms. The more detailed methodology developed by Jackie Stroud for AHDB (ibid.) provides the best current guidance for a more detailed study of earthworms, such as might be implemented where earthworm numbers were lower than expected (Review or Investigate groupings). An alternative way of assessing anecic earthworm populations is to count the numbers of middens on the soil surface (per $m^2$ area). Middens are the distinctive piles of organic residues (twigs, leaves, straw) gathered by each anecic earthworm during nightly foraging, the midden is placed directly over the entrance to the earthworm's permanent burrow. The method is described in Introduction to earthworms, AHDB Cereals & Oilseeds (2016).

The earthworm number data collected within the SBSH Partnership showed a range of values for each soil texture group in cropping systems (Table 14b). Review of these data did not suggest any need to change the benchmarking ranges for cropping systems proposed in Project 2 (Table 14a). The earthworm number data collected within the SBSH Partnership also show a range of values for each soil texture group in grassland systems (Table 15b). The original benchmarking ranges for grasslands proposed in Project 2 for a 20 x 20 x 20 cm block counted in the field were:

Depleted: 0 – 14; Intermediate: 15 – 29; and, Typical: ≥30.

The earthworm number data collected within the SBSH Partnership for grasslands showed higher numbers than within cropping systems, but the difference was not as large as predicted. Consultation with Jackie Stroud (SRUC) and a consultant actively using earthworm counts as part of a soil health monitoring and advice programme, together with reference to the data collected (Table 15b), led to a revised set of benchmarks with lower ranges for grasslands in the UK (Table 15a). These benchmarks also explicitly refer to the expectation that a typical active earthworm population within a grassland soil is likely to be composed of a number of ecotypes and a range of species.

*Soil organic matter (SOM)*

The approach used to derive the SOM benchmarks for testing within the SBSH Partnership was described in detail within Project 2. There are separate frameworks used for Scotland and for England and Wales. There is currently no recommended approach for Northern Ireland, though it should be possible to draw from work carried out by Teagasc for Ireland, together with the approach taken in Project 2 to develop categories and traffic lights for testing. An AHDB factsheet – Measuring and Managing Soil Organic Matter was produced in January 2019 and draft benchmarking tables for cropping systems were released for wider consultation alongside this factsheet. The benchmarking approach has been received very well by users.

There are a number of approaches to measure SOM – all are robust enough for soil health benchmarking, which is a comparative semi-quantitative approach, and all can be used to detect trends through time. Where the aim is to detect changes over time, it is important that the same method is used each time, as variations in the results from the same sample can result from the use of different temperatures, duration of heating and pre-treatments during laboratory analyses. Although data from research is often quoted as total soil organic carbon (SOC), it is possible to convert combustion measures of SOC to be expressed as SOM. Here the standard conversion factor is applied assuming that 1% total organic carbon equates to 1.72% soil organic matter; though it has been suggested this factor could be 1:2 (Pribyl 2010). However, these SOM data are not sufficient to support an assessment of soil C stocks for carbon benchmarking. Where carbon benchmarking is required, then intact soil samples of a known volume are needed so that bulk density and stoniness can also be determined accurately (Smith *et al.* 2019). However, the benchmarking approach used in the Soil Health Scorecard can help to identify sites where the SOM content is much lower than the expected equilibrium value for that soil texture/ climate combination and hence where changes in practice could be targeted to increase soil C storage. It is more likely that soils with low SOM (Review or Investigate groupings) would show an increase in SOM where management practices are implemented to increase organic matter additions e.g., through cover cropping, introduction of leys in arable rotations. The measurement of SOM and soil C is an area where new methods are emerging to describe the quality of the SOM (and the different types of OM present) alongside assessment of the total amount. Where soil clay content is known accurately, then examining the specific ratio of SOC to clay content can give extra information on the capacity of the soil to stabilise/ store SOM (Prout *et al.* 2020). However, in practice, it is difficult to get good measures of clay content – laboratory measures using laser diffraction are not well cross-calibrated at present and there are very large errors that can occur with chalk soils (Kerry *et al.* 2009). Hence currently, consultation with stakeholders has strongly supported the use of SOM (expressed as a %) for the Soil Health scorecard.

*England and Wales*

For England and Wales benchmarks are set according to topsoil texture (in the cross-compliance groups) and for regions (as a way of accounting for climate differences). There is a single benchmarking table for all lowland grasslands. The draft tables used integer values for SOM to define the ranges. However, during consultation, laboratories confirmed that they widely report SOM to customers at 1 d.p. and the tables were therefore redrafted to give the ranges at 1 d.p.
(Tables 16 – 18, Table 20).

**Table 16** Final recommended benchmarking table for use in the Soil Health scorecard, England and Wales, for soil organic matter (SOM, %) Cropping systems in low rainfall areas (E England)

| Traffic light | Light | Medium | Heavy | |
|---|---|---|---|---|
| Investigate | ≤1.0 | ≤1.7 | ≤2.2 | INVESTIGATE<br><br>Very low for the climate / soil type; may be associated with intensive cropping rotations with few organic matter inputs. In general, the simple rule is: add more organic materials, build more soil organic matter. Changes in SOM as a result of changes in practice can take a long time to detect. Consider whether crop residues can be returned and what sources of organic materials can be accessed. |
| Review | 1.1-2.1 | 1.8-3.3 | 2.3-4.4 | REVIEW<br><br>Lower than average for the climate/soil type; may be associated with intensive cropping rotations with few organic matter inputs. In general, the simple rule is: add more organic materials, build more soil organic matter. Changes in SOM as a result of changes in practice can take a long time to detect. Consider whether crop residues can be returned and what sources of organic materials can be accessed. |
| Monitor<br><br>Typical | 2.2-3.2 | 3.4-5.0 | 4.5-6.5 | CONTINUE ROTATIONAL MONITORING<br><br>Typical for the climate/ soil type; likely to be associated with crop residue returns and other regular organic matter inputs e.g. through cover cropping or compost. Changes in SOM as a result of changes in practice can take a long time to detect. There is no clear evidence for a critical value of SOM. Ensuring there are regular additions of organic matter to 'feed' the soil is more important than achieving any particular measured value. |
| Monitor<br><br>High | ≥3.3 | ≥5.1 | ≥6.6 | CONTINUE ROTATIONAL MONITORING<br><br>Above average for the climate/soil type; likely to be associated with crop residue returns and other regular organic matter inputs, including ley-arable rotations. Many well-established conservation agriculture or organic farming systems would appear in this group. Ensuring there are regular additions of organic matter to 'feed' the soil is more important than achieving any particular measured value. |

**Table 17** Final recommended benchmarking table for use in the Soil Health scorecard, England and Wales, for soil organic matter (SOM, %) Cropping systems in mid rainfall areas (NE England, Midlands, S England). Full descriptive text for the traffic light categories is given with Table 16.

| Traffic light | Light | Medium | Heavy | |
|---|---|---|---|---|
| Investigate | ≤1.0 | ≤1.9 | ≤2.7 | INVESTIGATE |
| Review | 1.1-3.0 | 2.0-4.0 | 2.8-5.2 | REVIEW |
| Monitor<br>Typical | 3.1-4.5 | 4.1-6.0 | 5.3-7.6 | CONTINUE ROTATIONAL MONITORING |
| Monitor<br>High | ≥4.6 | ≥6.1 | ≥7.7 | CONTINUE ROTATIONAL MONITORING |

**Table 18** Final recommended benchmarking table for use in the Soil Health scorecard, England and Wales, for soil organic matter (SOM, %) Cropping systems in mid rainfall areas (SW England, NW England, Wales). Full descriptive text for the traffic light categories is given with Table 16.

| Traffic light | Light | Medium | Heavy | |
|---|---|---|---|---|
| Investigate | ≤1.3 | ≤2.5 | ≤3.6 | INVESTIGATE |
| Review | 1.4-3.7 | 2.6-5.0 | 3.7-6.2 | REVIEW |
| Monitor<br>Typical | 3.8-6.1 | 5.1-7.5 | 6.3-8.8 | CONTINUE ROTATIONAL MONITORING |
| Monitor<br>High | ≥6.2 | ≥7.6 | ≥8.9 | CONTINUE ROTATIONAL MONITORING |

**Table 19** Summary of SOM data from Soil Health scorecard database collated in Project 9

| | **Cropping** | | **Grassland** | |
|---|---|---|---|---|
| **Texture group** | Range | Average | Range | Average |
| Heavy | *3.3 – 14.3* | *7.1* | *6.1 – 12.0* | *8.5* |
| Medium | *1.9 – 12.9* | *5.4* | *4.4 – 33.1* | *10.1* |
| Light | *1.2 – 7.0* | *3.1* | *2.7 - 7.3* | *5.2* |
| Shallow soils | *4.7 – 11.5* | *7.5* | | |

**Table 20** Final recommended benchmarking table for use in the Soil Health scorecard, England and Wales, for soil organic matter (SOM, %). Grassland systems in all climate regions.

| Traffic light | Light | Medium | Heavy | |
|---|---|---|---|---|
| Investigate | ≤2.1 | ≤3.4 | ≤4.6 | INVESTIGATE<br><br>Very low for the climate / soil type. Intensively-managed or recently established grasslands may have had relatively low returns of organic matter to the sward. If the soil is regularly poached or very compact then organic matter will not have been easily incorporated into the soil through biological activity. In general, the simple rule is: add more organic materials, build more soil organic matter. However, changes in SOM as a result of changes in practice can take a long time to detect. |
| Review | 2.2-4.9 | 3.5-6.4 | 4.7-7.6 | REVIEW<br><br>Lower than average for the climate/soil type. Intensively-managed or recently established grasslands may have had relatively low returns of organic matter to the sward. If the soil is regularly poached or very compact then organic matter will not have been easily incorporated into the soil through biological activity. In general, the simple rule is: add more organic materials, build more soil organic matter. However, changes in SOM as a result of changes in practice can take a long time to detect. |
| Monitor<br><br>Typical | 5.0-7.9 | 6.5-9.3 | 7.7-10.5 | CONTINUE ROTATIONAL MONITORING<br><br>Typical for the climate/ soil type; likely to be associated with well drained grassland at near neutral pH with well-managed returns of manures through grazing and targeted applications. There is no clear evidence for a critical value of SOM. Ensuring there are regular additions of organic matter to 'feed' the soil is more important than achieving any particular measured value. |
| Monitor<br><br>High | 8.0-14.9 | 9.3-19.9 | 10.6-19.9 | CONTINUE ROTATIONAL MONITORING<br><br>Above average for the climate/ soil type; likely to be associated with well drained grassland at near neutral pH with well-managed returns of manures through grazing and targeted applications. In some cases, accumulation of undecomposed SOM at the surface may give values in this range indicating some deterioration in pH or drainage (e.g. due to compaction). Ensuring there are regular additions of organic matter to 'feed' the soil is more important than achieving any particular measured value. |
| Review | ≥15.0 | ≥20.0 | ≥20.0 | REVIEW<br><br>Organic matter is accumulating at the surface. The soil may be an organic or organo-mineral soil type; these benchmarks do not apply to such soils. If this is a mineral soil, then accumulation of organic matter at the surface often indicates poor biological activity due to acidity or wetness. |

Shallow calcareous soils (mainly Andover series) of silty clay loam texture (falling across the medium / heavy boundary) showed a similar mean soil organic matter (SOM, %; Table 19) to heavy soils. Rowley *et al.* (2018) showed that exchangeable Ca ($Ca^{2+}$) can form complexes with organic compounds in soil and thereby provide an additional mechanism for stabilisation of SOM in these soils.

*Scotland*

By using the specific location for a sampling site in Scotland, the JHI Soil Information System database (http://sifss.hutton.ac.uk/SSKIB_Stats.php) identifies the main expected soil series. Hence the SOM thresholds can be related to this detailed and extensive database, which provides data that are relevant for each particular soil type and location. The database gives the main soil series and ranges of SOM for each soil series (with the lower quartile and median SOM at 1 d.p.), from which the thresholds can be generated. This approach is unchanged from Project 2.

**Table 21** Final recommended benchmarking approach for use in the Soil Health scorecard, Scotland, for soil organic matter (SOM, %). For each soil series, where data exists in the JHI Soil Information Systems Database, the data would then be allocated to traffic light groups based on the measured range of SOM.

| Traffic light | | |
|---|---|---|
| Investigate | Below lower quartile | INVESTIGATE |
| Review | Between lower quartile and median | REVIEW |
| Monitor | Above the median | CONTINUE ROTATIONAL MONITORING |

*Microbial activity measures*

The size and activity of soil microbial biomass is considered to be a key indicator of soil biological health (Project 2). However, the 'standard' method to determine soil microbial biomass which uses a chloroform extraction is not currently offered by any of the main commercial labs in the UK due to the hazardous reagents required. Two commercially-available alternative methods can be used to infer the size and activity of the microbial community: (i) potentially mineralisable nitrogen (PMN) which measures the amount of N readily decomposed under controlled (anaerobic) conditions, and (ii) $CO_2$-C burst which measures the amount of C released as $CO_2$ when a dried soil is rewetted. These processes are both dependent on the size and activity of the soil microbial biomass. The methods are currently delivered by commercial laboratories in the UK. The interpretation frameworks (or guideline values) developed in the United States were reviewed in Project 11 using UK data to derive guideline values that are relevant for UK agro-climatic conditions. Groupings and traffic lights for PMN and $CO_2$-C burst are given in the Project 11 report.

Discussion with farmer groups with a large proportion of calcareous soils (e.g. the Wallop Brook Farms' cluster, ORC Livewheat sites) highlighted unexpectedly low $CO_2$-C burst on high pH soils. When the data were collated for all more detailed Soil Health scorecards where $CO_2$-C burst had been measured, this anomaly is seen (Figure 6). The data collected for the maintained pH plots at Craibstone shows a similar trend with measured $CO_2$-C burst of 124, 140 and 101 mg/kg for the pH plots at pH 6, 6,5 and 7.5 respectively (see more detail in Project 4). Discussion with the laboratories using this methodology also highlighted that they were undertaking further studies in calcareous soils to determine whether evolved $CO_2$ was being re-adsorbed by the soil before detection. Care is therefore needed when interpreting $CO_2$-C burst data for calcareous soils. No similar pattern is seen for PMN which has a weak positive correlation with pH (Figure 7).

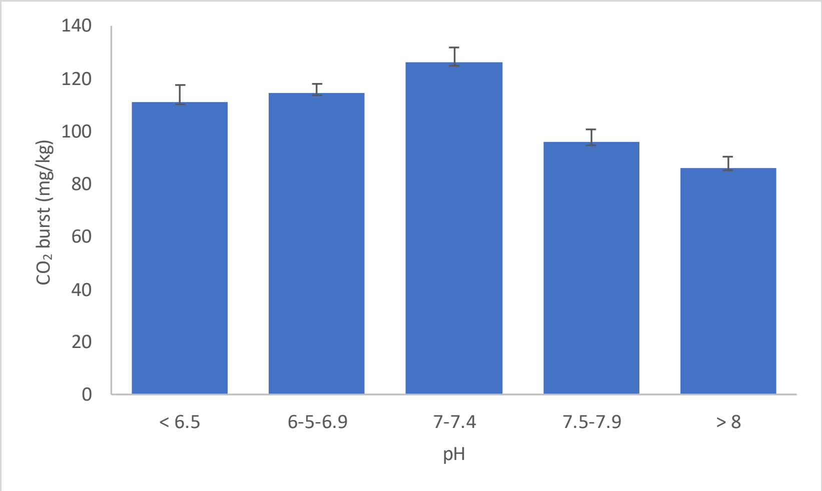



**Figure 6:** Mean measured $CO_2$-burst by pH; soils are grouped into 0.5 pH unit groups. This gives 12-28 samples for each group.

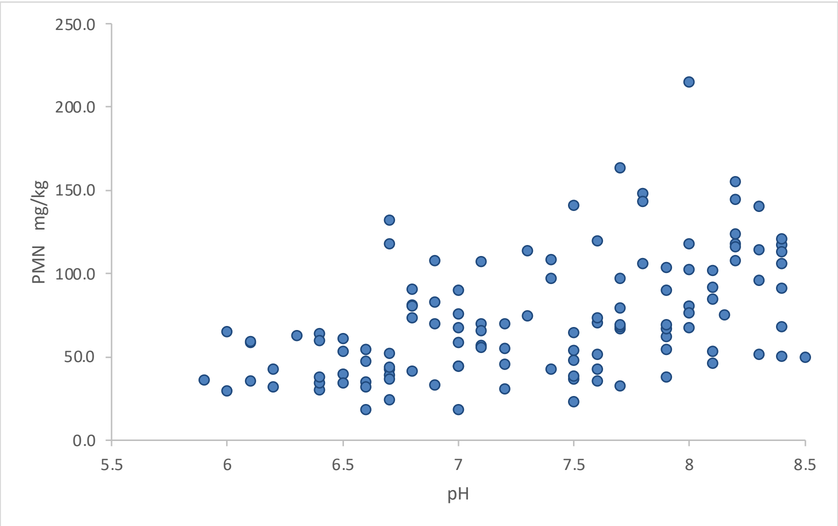



**Figure 7:** PMN plotted against pH; there is a weak positive correlation; r = 0.33

## 4.5. Impacts of soil management practices

The collated scorecard data provoked interesting discussions in the farmer research-innovation groups about different management systems and their impacts. Photo records of VESS blocks and of earthworms (sorted by size; Figure 8) were highly valued as a record. The groups especially valued comparisons of the same soil type (ideally the same series) across contrasting managements (see examples for the farmer research-innovation groups, Figures 9, 10, 11, 12). Farmers found it useful to revisit the basics of pH, drainage, and organic matter addition – alongside discussions about the latest monitoring or application technologies. To support discussion, the results of the Soil Health scorecard were used together with the management impacts tool (Project 1, as evaluated in Project 6) to allow identification of the soil-improving practices that were most relevant and most likely to have a positive impact in the specific soils and farming systems.

**Figure 8** Example of worm populations from sites on medium soils with regular organic matter inputs (manures, crop residues) but contrasting tillage systems - conventional (left) and zero till (right) showing the beneficial effects of reduced tillage on the large deep-burrowing earthworm species.

| Site characteristics | Rotational cropping Soil texture class | Field A, Farm 1 Cropping - rotation including late harvested crops Light | | Field B, Farm 2 Cropping - rotation including leys Light | | Field C, Farm 3 Cropping - rotation including late harvested crops Light | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 2018 | | 2020 | |
| Physical | VESS | 2 | Monitor | 2 | Monitor | 2 | Monitor | 2 | Monitor |
| Chemical | pH | 6.7 | Monitor | 6.9 | Monitor | 7 | Monitor | 6.6 | Monitor |
| | P | 40.6 | Monitor | 59.6 | Review | 37.2 | Monitor | 38.2 | Monitor |
| | K | 158 | Monitor | 106 | Review | 148 | Monitor | 264 | Monitor |
| | Mg | 82 | Monitor | 89 | Monitor | 144 | Monitor | 111 | Monitor |
| Biological | Earthworms | 13 | Monitor | 8 | Review | 1 | Investigate | 8 | Monitor |
| | SOM | 3.4 | Monitor | 2 | Review | 2.2 | Review | 2.5 | Review |
| Other | Ca | 1482 | | 1010 | | 816 | | 705 | |

When the results were discussed in the local farmer research-innovation group, the farmer confirmed that Field A had higher SOM as a result of previous long-term inputs of farmyard manure and composts; the value of this added organic matter can still be seen in SOM and earthworm numbers. The current cropping system with field vegetables now includes cover crops to try and maintain the SOM levels.

In Field B, potassium (K) has reduced under the mixed cutting/ grazing management in the 3 year grass-ley in this mixed system because of the high offtakes of K in silage.

Field C, had grown potatoes in 2017; the low earthworm numbers in 2018 are probably as a result of the intensive cultivations associated with that crop.

From 2018, Farm 3 implemented a range of measures to target improvements to soil health, especially integration of cover crops and reducing tillage intensity across the rotation. These changes may be leading to the increasing SOM but longer-term monitoring is required to verify this trend. The field is rotationally limed just ahead of potatoes and received lime overwinter following the 2020 sampling.

**Figure 9** Example scorecards sampled in November 2018 for fields on light soils (c. 56% sand, 35% silt, 9% clay) of the same soil series in the Midlands (mid-rainfall region) with information about group discussion.

| Site characteristics | Rotational cropping Soil texture class | Field D, Farm 4 Grassland – permanent pasture Light | | Field E, Farm 5 Grassland – permanent pasture Light | | Field F, Farm 6 Grassland – intensively managed Light | | Field G, Farm 7 Grassland – intensively managed Light | | Field H, Farm 8 Cropping – combinable crops Light | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Physical | VESS | 2 | Monitor | 2 | Monitor | 2 | Monitor | 2 | Monitor | 2 | Monitor |
| Chemical | pH | 6.0 | Monitor | 6.5 | Monitor | 6.1 | Monitor | 6.3 | Monitor | 6.5 | Monitor |
| | P | 3.6 | Investigate | 5.0 | Investigate | 27.8 | Monitor | 20.8 | Monitor | 35.4 | Monitor |
| | K | 27 | Investigate | 50 | Investigate | 90 | Review | 255 | Monitor | 199 | Monitor |
| | Mg | 28 | Review | 158 | Monitor | 65 | Monitor | 85 | Monitor | 51.6 | Monitor |
| Biological | Earthworms | 8 | Investigate | 12 | Review | 22 | Monitor | 16 | Review | 14 | Monitor |
| | SOM | 8.3 | Monitor | 7.3 | Monitor | 5.3 | Monitor | 7 | Monitor | 4.6 | Monitor |
| | PMN | 54.9 | Monitor | 61.2 | Monitor | 102 | Monitor | 69 | Monitor | 34.6 | Review |
| Other | Ca | 756 | | 855 | | 1420 | | 1160 | | 807 | |

The group chose sites to give a gradient of management intensity. Farm 4 is a low-input grazing system with sheep. The neighbouring farm (Farm 5) is also a low-input sheep system but has implemented a holistic planned grazing approach for c. 3 years. This has included targeted applications of Mg, as well as a move away from set stocking. The difference in available soil Mg can be seen. Farms 6, 7 and 8 use P and K fertilisers rotationally. Farm 6 is a mixed cattle/sheep farm with moderate intensity grazing which has been integrating diverse leys (Field F sampled was a second-year diverse ley). The neighbouring farm (Farm 7) is a dairy farm with moderate intensity grazing of rye-grass pastures (Field G). The higher microbial activity and earthworm numbers under the diverse ley were a focus for discussion; the group recognised that more data were needed to draw firm conclusions. The cropping system (Farm 8) had lower SOM and microbial activity; different benchmarks are used for SOM, earthworms and microbial activity (PMN) in cropping and grassland systems.

**Figure 10** Example scorecards sampled in 2018 /2019 for fields on light soils (sandy loam), very likely to be of the same soil series (Wick) in the southern part of the Eden Valley, Cumbria (high rainfall region) with information about group discussion.

| Site characteristics | Rotational cropping<br>Soil texture class | Field I, Farm 9<br>Cropping - rotation including leys<br>Medium | | Field J, Farm 9<br>Cropping – combinable crops<br>Medium | | Field K, Farm 9<br>Cropping - rotation including leys<br>Medium | | Field M, Farm 10<br>Cropping – combinable crops<br>Medium | |
|---|---|---|---|---|---|---|---|---|---|
| Physical | VESS | 3 | Review | 3 | Review | 2 | Monitor | 2 | Monitor |
| Chemical | pH | 6.1 | Review | 6.1 | Review | 6.6 | Monitor | 6.7 | Monitor |
| | P | 19 | Monitor | 21 | Monitor | 21 | Monitor | 23 | Monitor |
| | K | 142 | Monitor | 217 | Monitor | 125 | Monitor | 235 | Monitor |
| | Mg | 141 | Monitor | 91 | Monitor | 149 | Monitor | 179 | Monitor |
| Biological | Earthworms | 4 | Review | 8 | Review | 13 | Monitor | 6 | Review |
| | SOM | 4.9 | Review | 4.7 | Review | 4.1 | Review | 6.8 | Monitor |
| | PMN | 38 | Monitor | 35 | Monitor | 66 | Monitor | 44 | Monitor |
| Other | Ca | 1510 | | 1218 | | 1185 | | 1325 | |

Farm 9 is a mixed farm with rotational use of manures in north Shropshire. Field I and Field J were selected for comparison to explore the impact of the ley in the rotation (within 3 years for Field I, and >5 years for Field J). Farm data showed that the inclusion of the ley also increased the intensity of tillage operations in the rotation which may offset some of the expected value of including a ley. The farm had also recently used SOM data to target manure applications. Field K was at a comparable rotational stage to Field I but had recently received manures (dominantly FYM) in the cropping phase of the rotation. Earthworm numbers and microbial activity (PMN) were higher in Field K; the group recognised that more data were needed to draw firm conclusions about how to use manures most effectively to underpin both nutrient management and soil health goals. The group identified a site with comparable soil type with much lower tillage intensity (Farm 10 in the North-East, under no-till management for 3 years but with few OM inputs). This comparison also stimulated discussion about the role of long-term site history (not known for either farm) in determining baseline SOM levels, as well as the impact of pH. Data from the Craibstone long-term experiments (Project 4) were also explored by the group.

**Figure 11** Example scorecards sampled in 2019/2020 for fields on similar medium soils (clay loam c. 50% sand, 25% silt, 25% clay) in the Midlands and North-East of England (mid-rainfall area) with information about group discussion.

| Site characteristics | Rotational cropping Soil texture class | Field M, Farm 11 Cropping - rotation including leys Heavy | | Field N, Farm 11 Cropping – combinable crops Heavy | | Field O, Farm 12 Cropping – combinable crops Heavy | | Field P, Farm 13 Cropping – combinable crops Heavy | | Field Q, Farm 14 Cropping - rotation including leys Heavy | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Physical | VESS | 4 | Investigate | 4 | Investigate | 3 | Review | 3 | Review | 2 | Monitor |
| Chemical | pH | 8.4 | Review | 8.3 | Review | 7.7 | Review | 8.3 | Review | 7.2 | Monitor |
| | P | 10.2 | Investigate | 19.8 | Monitor | 16.0 | Monitor | 14.6 | Review | 14.6 | |
| | K | 184 | Monitor | 226 | Monitor | 70 | Review | 224 | Monitor | 195 | Monitor |
| | Mg | 60 | Monitor | 62 | Monitor | 36 | Review | 98 | Monitor | 67 | Monitor |
| Biological | Earthworms | 4 | Review | 5 | Review | 4 | Review | 10 | Monitor | 11 | Monitor |
| | SOM | 5.7 | Monitor | 5.4 | Monitor | 4 | Review | 5.6 | Monitor | 8.2 | Monitor |
| | PMN | | | | | 32.5 | Review | 51.9 | Monitor | | |
| Other | Ca | 3885 | | 4730 | | 2161 | | 3916 | | 3280 | |

All these soils have naturally high pH and usually higher than average levels of extracted soil Ca (typically 1000 - 2500 ppm) as a result of the soil parent material; the soils are also naturally low in P with moderate/high potential for reduction in P use efficiency from added fertiliser due to the high Ca. The soils show self-structuring properties but are also vulnerable to structural damage if trafficked when soil water content is above the plastic limit. Farms 11 and 12 were collecting baseline data on soil health to inform their changing soil management strategies. The farmer reported improvements in VESS and earthworm numbers especially in a diverse ley (cover crop). Data were compared with those collected from Farm 13 (reduced tillage, integrated cover cropping) and Farm 14 (organic farm with moderate intensity tillage and use of livestock manures) to provide benchmarks on similar soils. Longitudinal monitoring is needed to explore whether these positive outcomes (improved physical and biological indicators) are realised. We had hoped to revisit Farm 11 in autumn 2021 but were prevented by Covid on-farm, as well as the general restrictions in place.

**Figure 12** Example scorecards sampled in 2018/2019 for fields on heavy soils (40-45% clay), of the same or similar soil series over chalky boulder clay in the East of England, (low rainfall region) with information about group discussion.

When the Soil Health scorecard approach was rolled out to the AHDB Monitor Farms, six sites per farm were used to allow some within-season comparisons of the impact of soil type within the same management system and/or to compare management practices within the same soil type. Selection of the sites was always done in conjunction with the farm manager so that the data were able to support conversation about soil type/ management interactions and also provide some robust baseline data for the farm. The use of the Soil Health scorecard to support discussions about soil management at Monitor Farm virtual meetings was captured during 2020 and 2021; e.g. for the Northampton Monitor Farm https://youtu.be/PzcX1rpa3C0 and for the Penrith Monitor Farm https://youtu.be/zNRu_OUvhVY.

The farmer groups were interested to see if crop yield or other management data could be linked to the Soil Health scorecard measures. Within their farms/fields, farmers were able to identify better and worse yielding areas, and in most cases, they linked these to differences in inherent soil properties (soil type - texture, depth, stoniness) and the impacts of these factors on seedbed preparation or drought/waterlogging risk. However, based on their experience, the farmer research-innovation groups felt that weather (affecting drilling timing and conditions, disease risk and grain fill *inter alia*) had a bigger impact than soil conditions. Most farmers were aware of the concept of yield potential (largely driven by plant capture of water and solar radiation) as explored in more detail in the Yield Enhancement Networks (YEN; Sylvester-Bradley and Kindred 2014). Collation of farm management records within the project was prioritised for sites where field yields were recorded. 28 participating farmers (94 Soil Health scorecard sites) agreed to share farm records, including rotational yield data with the project. Twelve farmers returned complete records (45 Soil Health scorecard sites, 35 with field-scale yield records) in a variety of formats, including paper notes, and with a range of levels of detail within farm management software. Where farm management software was used, there were usually good records of agrochemical inputs and fertiliser use, but records were more patchy for tillage operations, organic material applications, residue management and yield. In some cases, the farms used separate spreadsheets to record some of this information and these were obtained on request. Given the limited yield data available and the range of crops present, it was not possible to create a simple relative yield measure that could be used across sites and seasons to compare with the Soil Health scorecard. Modelling yield data in terms of site yield potential and across different crops to give a rotational yield index may provide a way of establishing a yield measure that could be compared with the Soil Health scorecard measures across sites, but this was beyond the scope of this project.

Review of the outputs of the descriptive model developed in Project 1 fitted with the farmers expectations of the expected trajectory of changes in soil health (and other factors) in response to the management changes described. However, the outworking of these impacts on the observed

Soil Health scorecard measures were not always easily seen in the site comparisons within the farmer research-innovation groups (see examples in the discussion of data as part of Figures 8, 9, 10, 11). The groups recognised that in the field, often in contrast to experimental trials, multiple practices are implemented dynamically through the rotation and that their impacts might interact (for example, inclusion of a ley also increased the intensity of tillage operations within the rotation, Figure 11). Practices that had been adopted on farm 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. As part of the discussions, the farmer research-innovation groups discussed and reviewed the qualitative assessment of the benefits and costs of implementation associated with individual soil-improving practices reported by earlier farmer discussion groups (Stockdale and Watson, 2012) considering and supported the findings.

## 5. Conclusions

During the lifetime of this project there has been a strong and growing farmer interest in the topic of soil health and specifically in looking for effective management options to improve / maintain soil health. This project has confirmed the findings of Krzywoszynska (2019) that farmers and scientists share a concern with soil degradation, and recognise that how soil health will be addressed is both a technical question (what can be done?), as well as a cultural question (what is worthwhile doing on my farm?). The SBSH Partnership benefited from active farmer engagement from across the UK with a range of systems, farm sizes and locations. The farmers working together in farmer innovation-research groups have included growers confident that they had identified and were implementing soil-improving management practices, together with those who were not sure that their actions were positive for soil health. Farmers within the groups have implemented a range of practices, at least partly to improve soil health. These are mainly system-oriented approaches (i.e., increasing OM input, reducing tillage intensity, increasing cropping/sward diversity); but have also included some tactical interventions, such as slurry inoculation, application of molasses or compost teas; companion cropping and CTF systems. Consequently, while the project sought to evaluate and co-produce the Soil Health scorecard, a technically-based approach to supporting and informing effective decision-making, the willingness of the groups to share information has enabled significant co-learning within the groups about the opportunities and challenges both for soil management and more widely within farming systems. As intended, direct engagement with the farmer groups during the process also helped to shape the SBSH Partnership outputs, identify research and KE gaps as well as to shape new research questions.

The farmer innovation-research groups found the field protocol relatively easy to follow, especially when shown (as part of field days) and when it was developed so it could be seen (as a video reminder) rather than solely read. When the principles and the protocol were described to growers in other systems (perennial row crops), they were rapidly able to adapt the protocol and then apply the new protocol effectively within their own systems. Farmers from the groups were willing to collect data in their own fields; numbers were constrained by the number of analyses that could be supported by the project budget rather than the number of volunteers. The farmer groups confirmed that although the timing of sampling when soils are moist and warm (mid-autumn / early spring) was not ideal, in terms of a fit to a lull in farm workload, it could be implemented in practice. This was confirmed by >80% completion of the agreed field data collection and sampling submission processes. As anticipated, weather and farming demands, and sometimes personal commitments, meant not it was not possible to achieve 100% delivery.

The project only provided an opportunity for the farmer innovation-research groups to implement a few snapshot measurements. However, groups discussed how the regular monitoring of soil health could be integrated into farm practice. Across all groups, the most common rotational crop is a first cereal (often, but not always winter wheat). The groups that were sampling in cropping systems therefore sought to match their sampling across the group to post-harvest in the stubble or cover crop after a cereal and after the soil has wetted up (usually October/November) , to allow the most effective benchmarking between fields/farms. Within farms, farmers used their knowledge of the differences in inherent soil properties to select sampling sites within the project. For many farmers the intention was to select sites that would continue to be monitored in the future as network of farm sites alongside other targeted sampling e.g. for nutrient management or tillage optimisation.

The farmer groups helped to ensure that the approach to assessment and data recording was both simple and clearly structured. Simple paper recording forms were felt to guide the process. In this project the pilot field-based app that was tested didn't work very well with muddy fingers, but farmers recognised that having a clear interface to enter data would be of value and some were aware of other soil data collection apps, such as SoilMentor. The recommended indicators together provide a soil health scorecard which integrates physical, chemical and biological aspects to give a snapshot overview of soil health akin to a routine car safety check (MOT) or school report. Farmers liked the overall scorecard and confirmed that it gave a useful visual health check – some indicated that they would also like to see a single soil health score. Farmers particularly valued the VESS scoring and considered that capturing photos provided a clear record and often gave further information when reviewed in the office that could be missed in the field. Overall, consultation and review supported the use of the multi-factorial framework and no indicators were removed. The work in Project 12 and here confirmed that adding an indicator of microbial activity to the Soil Health scorecard potentially gives some additional detail on soil function at relatively little extra cost. However, care is needed to interpret and use the data for the UK. Review of the indicators in light of the data collected in the project has led to:

- Reduced thresholds for the earthworm number benchmarks in grassland.
- Strong confirmation of the value to farmers and advisors in providing simple benchmarks for SOM; minor updates were made in the presentation of the benchmarking tables compared with those presented during the project for consultation.

Farmers recognised that just knowing some numbers about soil, even having an integrated assessment of physical, chemical and biological properties with comparison to relevant benchmarks won't improve soil health. In the project, the Soil Health scorecards collected by the farmers supported informed discussion within and across farmer innovation-research groups about the range of soil management practices already used and the practices that might be adopted to maintain/ improve soil health. Situations where farming pressures might compromise soil health (e.g., supply chain requirements leading to harvest of root crops from wet soils) were also identified. The most productive discussions often emerged where results didn't always show the simple trends that were expected, as a result of interactions with inherent soil properties, and/or interactions between the impacts of different management practices e.g., OM additions and tillage intensity. In particular, the groups valued the way the presentation of data within the Soil Health scorecard quickly identified areas where improvement can be made through management or where more detailed assessments or more regular monitoring are needed to clarify the problem. The discussions in the farmer innovation-research groups fed into separate work facilitated by the SBSH Partnership team for the UK Soil Health initiative to identify best (and least-worst) practices that minimise deleterious impacts on soil quality, particularly for productivity and in relation to direct impacts on air and water quality. This co-produced information on sustainable soil management has been brought together in farmer-facing resources for many soils and farming systems: www.cfeonline.org.uk/environmental-management/soils/uk-soil-health-initiative-guides/. Overall, the discussion with farmer innovation-research groups highlighted that although general guidance is useful to inform practice choice, the best soil husbandry is always site and season-specific, and each action needs to be informed by observation.

Farmers valued the evidence emerging from research trials of links between improved soil health (or soil-improving practices) and increased yield (Project 4). However, farmers quickly recognised that even within a farm or farmer innovation-research groups, it was difficult to separate the impacts of season, inherent soil factors and soil health on on-farm yields. Now that the Soil Health scorecard is in place, it should be possible to integrate its use into other studies e.g. looking at achievement of yield potential, yield resilience and/or the delivery of other ecosystem goods/ services. Such approaches should enable an increased understanding of the links between land management, soil properties and soil functions, with appropriate consideration of spatial and temporal distribution, in order to optimise the delivery of all ecosystem services in the landscape.

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# 8. Appendices

## APPENDIX 1

**Farmer research-innovation groups - sampling protocol - autumn 2020**

**Background**

Soil observations and samples are collected on farm for a number of distinct purposes – e.g. checking the performance of fertilisation/liming strategies, planning new fertiliser applications, determination of timeliness for cultivations. This protocol is intended to fit within those approaches but not necessarily to replace them all; on any farm, there are likely to be further but complementary approaches to soil characterisation e.g. grid sampling of soil P/K for precision fertiliser management.

**The overall aim of soil observation and sampling in the on-farm studies within the Soil Biology and Soil Health Partnership is to:**

- **pilot the use of a soil health scorecard approach (developed earlier in the Programme) to ensure that it provides farmer-friendly soil assessment; and,**
- **bring these data on soil health together with management data to determine how the soil health dataset can be linked to crop yield constraints and their extent over 3 cropping years within on-farm rotations (2018-2021)**
- **explore the impact of contrasting management practices on soil biology and health in relation to crop yield.**

**Sampling timing**

We expect that regular sampling for soil health monitoring will take place once per rotation and at the same point in the rotation to maximise comparability between samples. Farmers will determine the best point in the rotation to integrate the soil health sampling.

Soil observation and sampling should take place at a time that is:

- after harvest, and
- after the topsoil has wetted up in the autumn, and
- at least 1 month after any cultivations / moderate soil disturbance.

This timing may mean that rotational sampling for soil health does not easily fit at all points of the rotation. In some rotations, this may mean sampling in an actively growing cover crop or after drilling of the next main crop.

Ideally the sample should not be taken within 3 months of application of organic inputs, though this may not be able to be avoided if manures/composts are applied annually.

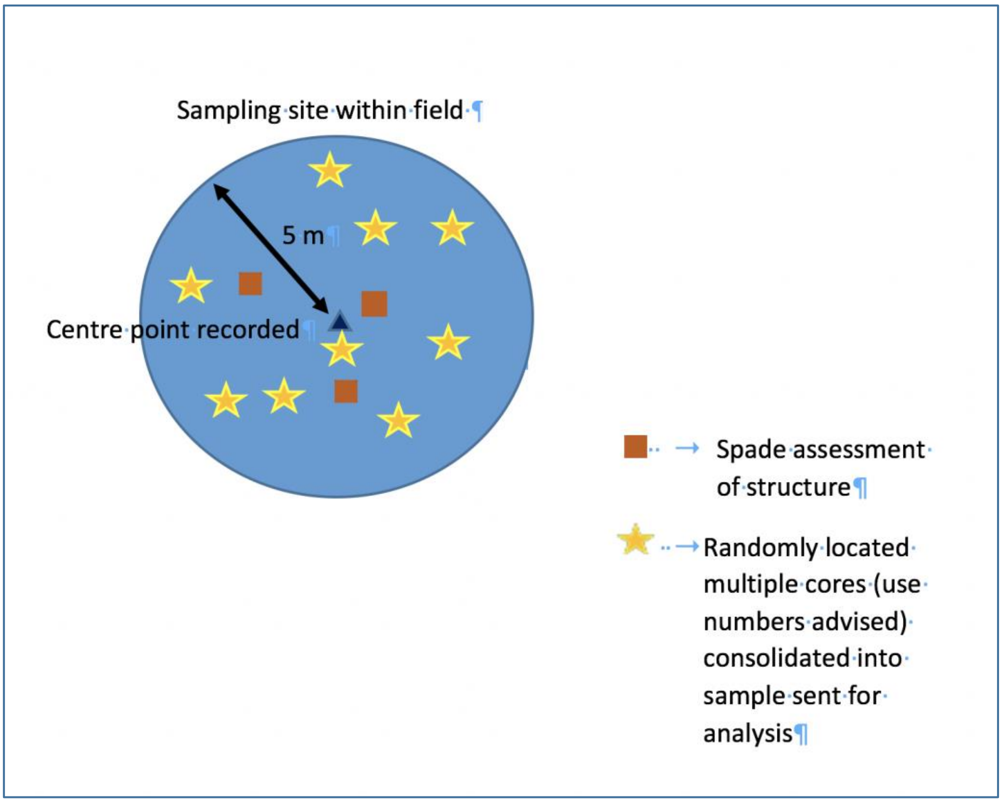
*Feedback from practice on this sample timing and the difficulty/ease of scheduling the sampling in this period is important for the SBSH Partnership.*

**Because samples have to be posted to the laboratory, think about the timing of the sampling carefully.**

**Site selection and characterisation**

The farmer is best-placed to determine their own representative sampling sites (within which soil texture and cropping show limited variation) and where these sites can provide useful data to monitor soil health and inform farm practice in soil management. We recommend that farmers sub-divide fields as needed into similar zones and that, where appropriate, each zone is sampled. There may be just one sample site per group of fields, or there may need to be several per field, where soil texture varies markedly. As for all soil sampling, the area selected should be relatively uniform. Avoid headlands, gateways, unless you are specifically targeting them as a sampling site, and also avoid marked wheelings where possible.

The location of the sampling site is recorded by its centre point and the sampling site is then considered to be the area within 5 m in all directions of that centre point i.e., a rough circle of 10 m in diameter. It is likely to be representative of a larger area.




**For each site you will be given an SBSH-xx number, please use this on all records / samples – together with any other identifier e.g. field name.**

Site locations should be recorded accurately.

Farmers with a Smartphone may want to drop pins for the sampling location in Google maps (just stick your finger on the screen for a long time!). This then gives you the latitude, longitude (e.g. 52.2231996, 0.0973464) and can be saved for future use with an appropriate name (X FIELD, SH sample).

We are also asking for records of basic land use and soil type information for sites chosen from simple pre-defined lists. This information is used to set up groups for comparisons of data from similar sites and with benchmarks.

**For each sample collected, please complete the sample form** and scan or take a photo and send to the SBSH Partnership team with any associated photos.

| Land use | Topsoil (key characteristic) |
|---|---|
| *Cropping – combinable crops* | *Calcareous (Y/N)* |
| *Cropping – rotation including late harvested crops* | *Sandy and light silty* |
| *Cropping – rotation including leys* | *Medium (clay loams)* |
| *Cropping – field-scale vegetables* | *Heavy (clays)* |
| *Grassland – intensively managed* | *Organic* |
| *Grassland – permanent pasture* | |

**In field assessments**

***Soil structure* – Visual Assessment (spade, VESS)**

3 soil structure assessments should be carried out in the field within 2 m of the centre point of the sample site at the same time as a soil sample is collected for analysis (see below).

Ideally the soil should be moist to 30 cm but not saturated; hence it is possible to do these assessments on a damp/rainy day – but not at the end of a run of rainy days!

The agreed soil structural assessment protocol is VESS ( www.sruc.ac.uk/vess ). The AHDB Healthy Grassland Soils field guide uses a near-identical approach and can also be used. This is a simple in-field assessment approach which requires a spade and a scorecard for comparison. The lowest score (Sq1) is given to the least compact and most porous condition, and the highest score (Sq5) to a very compact condition with very large and often platy aggregates with very low visible porosity.

The score (between 1 and 5) will be recorded on-site. **This is the score of the most limiting layer**. Different layers showing different structures may be observed to 25 cm, and a photo (e.g. via Smartphone) should be taken to be stored and named to match the sampling. The block should be photographed; ideally on a white background and with an appropriate scale (e.g. ruled measure, spade blade)

One integrated value is recorded for the site. Only whole number scores should be chosen; but add notes to add detail that is useful for you. e.g. surface very good tilth (1) overlies more blocky structure (2)

DETAILED PROCEDURE

i. Cut and clear away the crop to within 5 cm of the surface of the soil to be sampled.
ii. Loosen and excavate the soil around three sides of a ~20 x 20 cm block which will form a block of soil to minimise disturbance of the soil structure and soil surface when the block is dug out.
iii. Dig out a block a spade width square, approx. 20 x 20 x 25 cm deep with one undisturbed side.
iv. Place the block on a light coloured tray / board to help description.
v. Pick the soil face with a knife to expose structure and roots.

vi. Identify horizontal layers and record. Any layering may be difficult to distinguish visually, but may be identified by prodding with a picking blade (knife etc).

vii. Photograph the block, with a scale if possible.

viii. Break up the block if necessary. Note you may want to separate earthworms to be able to describe the groups founds and record worm numbers while doing this.

ix. Allocate a score for the condition of the structure, rooting and soil surface according to the best-fitting description from the categories given in the VESS chart. If the soil is strongly layered, allocate a score for each layer of soil.

x. The overall score recorded should be that of the most limiting layer (i.e. the highest score observed).

xi. A weighted mean score of all the different layers can also be calculated to give more detail. This allows for cases where there is a big difference between layers. This is done by multiplying the score of each layer by its thickness and dividing this total by the overall depth.

For example, in a two-layer block (25 cm deep) where 5 cm depth of intact soil (Sq2) lies over 20 cm of compact soil (Sq 4), the block has an overall score of:

$$\frac{(5 \times 2) + (20 \times 4)}{25} = \text{Sq } 3.6.$$

For on-site understanding of soil structural quality and the possible impacts of poor/good management, it is often useful to compare the structure at the sampling site with soils where trafficking is known to have had an impact – gateways, wheelings – and areas with expected good structure (e.g. close to hedges). This gives a site-specific understanding of what good and poor structures look like for that soil type. It is useful to keep a note about these observations as notes associated with the recorded score.

***Earthworms***

Using the VESS block or an adjacent block of soil, earthworms will be hand-sorted. The indicator requires numbers of adult earthworms and, for grassland, number of species. This will be achieved by hand-sorting of earthworms from a block of soil. It is very useful to observe which functional groups are present and to photograph the worms as a record. This is a background observation – more detailed earthworm counts can be made, see https://ahdb.org.uk/knowledge-library/earthworm-recording-sheet

PROCEDURE

i. If the VESS block cannot be used, cut and clear away the crop to within 5 cm of the surface of the soil to be sampled. Excavate a further block of soil 20 x 20 x 25 cm deep.
A different sized block can be used to reflect the size of your spade but make sure you record the size of the block used (height x width x depth cm).

ii. For the block of soil, break up any clods, and separate all adult and immature (no saddle visible) worms collected within up to 10 minutes. Then split the adult and immature worms, count them and set the adults aside to identify further.

iii. Use the AHDB guide to assign adult earthworms to functional groups https://cereals.ahdb.org.uk/media/1400472/h6-how-to-count-earthworms.pdf

iv. In grassland only, use the OPAL field guide to assign adult earthworms to species. https://www.opalexplorenature.org/sites/default/files/7/image/SOIL%204pp%20chart.pdf .

v. Photographing your worms can be a useful record.

*Added measures in the research trials*

In the research trials (Project 4), intact cores are also being collected for the measurements of micro-arthropods (0- 5 cm) and bulk density (from the mid-topsoil 5-10 cm). Because these measures require a specialised corer, they are not being included in the minimum data set collected on farm.

Similarly the penetrometer resistance to 40 cm using a penetrologger is not being included in the initial minimum dataset, as not all farmers will have access to this equipment.

***Soil sample collection***

Within the sample site (i.e. within 5 m of the centre point), **collect a representative soil sample** using the RB209 protocol (though walk whatever letter you fancy!). So that data can be compared with existing nutrient indices and their benchmarks, we will **use the recommended sampling depths from RB209**, 0-23 cm for reduced/ no till land, 0-15cm (or 23cm) for tilled land; 0-7.5cm for grassland. Bulk a number of small cores or trowel samples of soil into a bucket or large plastic bag, break the soil gently and ensure that it is well mixed to create a mixed representative site sample.

***Main soil analysis***

**The first subsample from the mixed representative site sample** of approximately 400 g fresh weight will be sent away for analysis. This is equivalent to two thirds of a medium grip seal bag.
The minimum dataset is:

- pH
- Extractable P
- Extractable K
- Extractable Mg
- Extractable Ca
- Extractable Na
- Organic matter (this will be measured by Loss on Ignition – and reported as organic matter rather than soil carbon)

***PMN – biological activity indicator***

We are also adding PMN to the analysis, as it is a promising indicator of biological activity. This will be compared with the $CO_2$-burst. Hence **we will need to send a second sub-sample** from the mixed field sample; put a mixed sample into the gripper bags, up to the lower white line approximately (about 400 g). These samples should be posted asap (and if posting is delayed by more than an hour or so, the sample should be stored in a fridge and posted within 48h).

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In the research trials (Project 4), microbial biomass C, nematodes and respiration (Solvita) are also being measured on soil samples. As part of project 5 & 6, DNA-based measures of soil biological communities are also being made. The findings from the research trials will be used to identify the most robust measures for testing as part of the Soil Health scorecard in the future.

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***Other possible in-field assessments***

*Deep-burrowing earthworm activity*

The deep burrowing (anecic) earthworms may not always be recovered when you dig a topsoil pit. An additional way of judging if you have a good population is to count the middens – these are the piles of residue and other materials gathered by the worms during foraging.

You may need to get your eye in to spot the middens, but then take an average count from three 1 x 1 m areas within your designated site. Each midden = one active burrow = 1 deep-burrowing worm.

Midden counting (anecic earthworms)

Middens are the distinctive piles of organic residues (twigs, leaves, straw, stones) gathered by each anecic earthworm from its nightly foraging activities

A fast way of assessing anecic earthworm populations is to count the numbers of middens on the soil surface (per m² area).

Field edges that receive tree litter often have higher anecic earthworm populations than in the centre of the field.

| | Typical number of middens per m² (in spring) |
|---|---|
| Ploughed soil | 0–3 |
| Minimum tilled soil | 3–15 |
| Zero tilled soil | >15–60 |

Moving the midden will reveal the entrance to the earthworm's permanent tunnel (up to 1 cm in diameter)

*Illustration from AHDB Cereals & Oilseeds (2016) Introduction to earthworms – accessed via* [*https://www.fas.scot/downloads/ahdb-an-introduction-to-earthworms-guide/*](https://www.fas.scot/downloads/ahdb-an-introduction-to-earthworms-guide/)

*Infiltration*
At its simplest, this means pouring on a known amount of water and seeing how long it takes for it to be absorbed by the soil. It is usually done within a tin or ring pushed into the soil. In fact, the bigger the ring the more robust the measurement. Because large rings are more difficult to manage in practice, usually the measurement is made with a ring about 15 cm diameter pushed into the soil by 5-10 cm and then with an addition of c. 500 ml of water.

> *A good demonstration of the ring test and associated observation of the soil structure from the US and how it might be used to compare two very differently managed sites on either side of a farm boundary* … https://www.youtube.com/watch?v=mu8ix4xuuCY

Lots of factors affect the infiltration rate (soil texture, recent rain/temperatures and many more). So it can be much harder to see differences even between two adjacent sites than the video suggests.

A useful tip is to make the measurement twice in the same tube. Often the second time gives a better indication of the real infiltration rate that is less dependent on recent weather, as the first test just wets the soil. If the soil is already quite saturated you may find there is very little difference in the first and second times. Also make sure you look at the soil in the tube once you've done the test – the distribution of water in the tube can also give important info. e.g. did the water just run away down big pores and barely wet the topsoil; is the water sitting in a layer just below the surface? Note that if you have compaction at 20 cm and the tube is inserted to 15cm then the compaction is unlikely to affect the infiltration rate measures as the water can spread out laterally once it reaches the bottom of the tube.

An excellent (if old) report on the issues and methods is given by Johnson (1963)
https://pubs.usgs.gov/wsp/1544f/report.pdf