January 2021

Annual Project Report
January 2020 to December 2020
No. 91140002-APR2020

Soil Biology and Soil Health Partnership

Elizabeth Stockdale[1], Anne Bhogal[2], Erika Wedgwood[3], Jenny Bussell[4], Joana Vicente[5], and Christine Watson[5]

[1]NIAB, Farming Systems Research, Huntingdon Road, Cambridge, CB3 0LE

[2]ADAS Gleadthorpe, Meden Vale, Mansfield, Notts, NG20 9PF

[3]ADAS Boxworth, Battle Gate Rd, Cambridge CB23 4NN

[4]Game & Wildlife Conservation Trust, Loddington House, Main Street, Loddington, LE7 9XE

[5]Fera Science Ltd., Sand Hutton, York, YO4 11LZ

[6]SRUC, Crop & Soils Systems, SRUC Aberdeen Campus, Craibstone Estate, Aberdeen AB21 9YA

This annual project report was produced as part of the five-year Soil Biology and Soil Health Partnership (AHDB: 91140002) that started in January 2017. The work is funded by a contract for £858,869 from AHDB and £140,934 from BBRO.

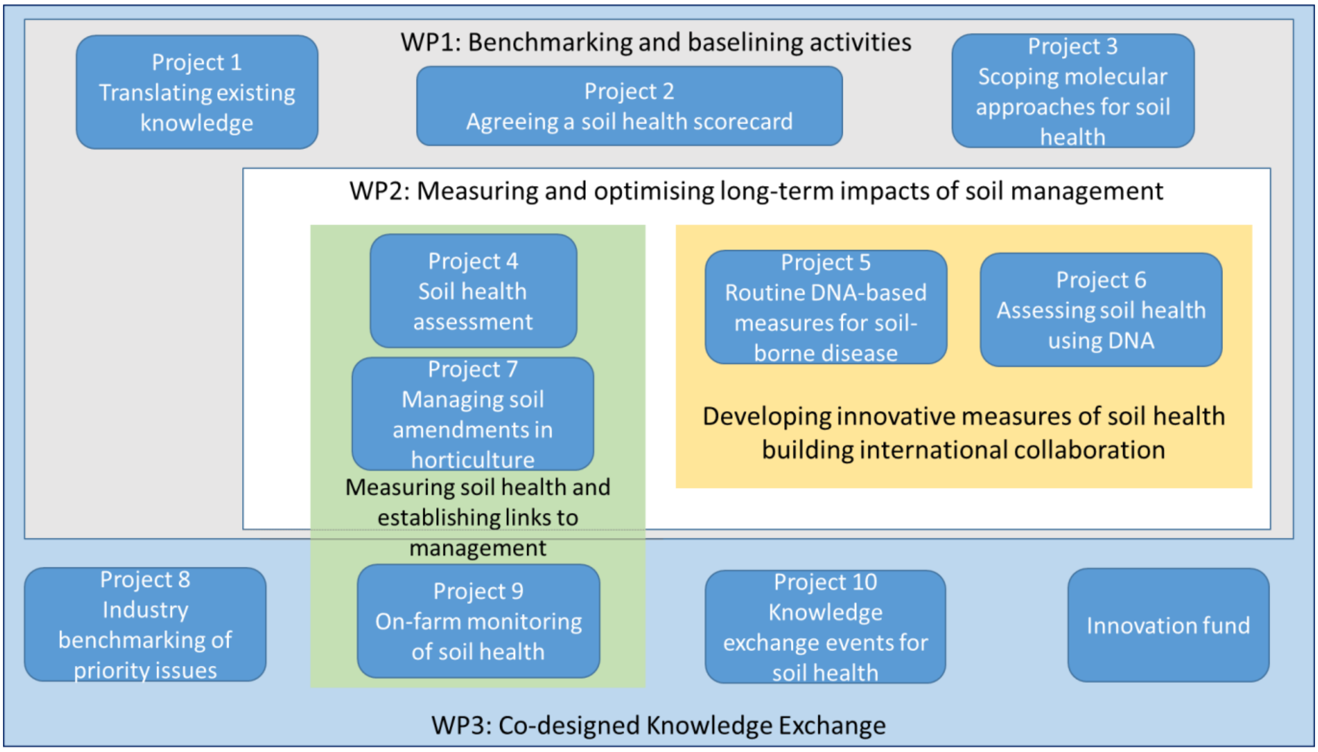
Soil Biology and Soil Health Partnership Annual Report
January 2020 to December 2020

PARTNERSHIP OVERVIEW

Funded by AHDB and BBRO, the Soil Biology and Soil Health Partnership is a five-year (2017-2021) cross-sector programme of research and knowledge exchange designed to help farmers and growers maintain and improve the productivity of UK agricultural and horticultural systems through better understanding of soil biology and soil health. The overarching aims are to:

- Improve on-farm understanding of soil health by sharing current academic and industry knowledge in usable formats
- Develop and validate indicators of soil biology and soil health in research trials and on-farm

The programme comprises a series of interlinked projects.



In 2020, Project 11 funded through the Innovation Fund was completed, with the final report published. Additional Projects 12, 13 and 14 were funded through the Innovation Fund.

GREATSOILS

British Beet BBRO Research Organisation

AHDB

COMPLETED PROJECTS

Project title	**Translating existing knowledge of management effects on soil biology and soil health for practitioners**		
Project number	91140002-01		
Start date	January 2017	**End date**	December 2017
Final report and supplementary information	Link to Final Report Link to supplementary information		

Project title	**Selecting methods to measure soil health and soil biology and the development of a soil health scorecard**		
Project number	91140002-02		
Start date	January 2017	**End date**	December 2017
Final report	Link to Final Report		

Project title	**Molecular approaches for routine soil-borne disease and soil health assessment – establishing the scope**		
Project number	91140002-03		
Start date	January 2017	**End date**	December 2017
Final report	Link to Final Report		

Project title	**Identifying current understanding, knowledge gaps and confirming the key priority issues in understanding and management of soil biology and health**		
Project number	91140002-08		
Start date	January 2017	**End date**	December 2017
Final report	Link to Final Report		

Project title	**Developing UK-relevant benchmarks for the soil health indicators: Potentially Mineralisable N (PMN) and Solvita CO_2 burst**		
Project number	91140002-11		
Start date	April 2019	**End date**	February 2020
Final report	Link to Final Report		

ONGOING PROJECTS

Project title	**Soil health assessment**		
Project number	91140002-04		
Start date	01/06/2017	**End date**	31/12/2021

Project aim and objectives
The overall aim of this project (Project 04) is to quantify the effects of contrasting management practices on soil biology and health in relation to crop yield and quality, and to evaluate the use of simple tools for assessing soil health. The specific objectives are: 1. To quantify the effects of contrasting management practices and resultant soil conditions (organic matter, drainage status, structure and pH) on crop establishment, yields and quality across rotations including cereals, sugar beet, potatoes, horticultural crops and grass leys. 2. To evaluate the effect of contrasting management practices on weed and disease pressures for each crop in the rotation. 3. To evaluate the effects of contrasting management practices on key measures of soil biological, physical and chemical health. 4. To explore links between soil biology, soil structure and crop productivity 5. To provide a test bed for the development of DNA-based soil health tests (Projects 05 and 06) 6. As part of the whole Soil Health Research Partnership programme, to translate the findings into simple measures of soil health, linked to measurable outcomes and practical management solutions (the integrated soil health scorecard).

Key messages emerging from the project
The prototype soil health scorecard has been successfully evaluated using data from two long-term experimental sites in 2019/20: the organic material amendment experiment at ADAS Gleadthorpe and the ‘Old Rotation’ experiment at SRUC Craibstone. At Gleadthorpe, soils which had received repeated application of a range of organic materials tended to score more favourably using the soil health scorecard compared to where only inorganic fertilisers had been applied. Soil organic matter, pH and nutrient status increased and VESS scores decreased (i.e. improved soil structure), with repeated additions of cattle FYM and green compost having the greatest impact. Crop yields tended to be highest where broiler litter had been applied. At Craibstone, not surprisingly, soil nutrient status was higher in the fertilised soils, but long-term fertilisation did not have an effect on SOM, pH or soil structure. Soil organic matter levels were highest for fertilised oats and roots, whereas earthworm numbers were greatest in the unfertilised grass ley and lowest in the root crop. As expected, higher yields were attained with fertiliser application for all crop types, with the greatest increases seen in hay yields. All treatments at this site scored either moderate (amber) or good (green) on the soil health scorecard.

GREATSOILS

British Beet BBRO Research Organisation

AHDB

Summary of results from the reporting year

A network of seven existing experimental sites with a history of different management practices and known differences in soil organic matter content, pH and drainage status/structure (key drivers of soil biological functioning) has been established covering a range of soil and agro-climatic conditions in Britain, and rotations that include grass leys, cereals, sugar beet and potatoes. These sites provide the test bed for the methods confirmed from Project 2, and facilities to test and develop the molecular-based techniques (Projects 05 and 06).

The following soil quality parameters are being evaluated at each of the sites (with sampling staggered across the lifetime of the project): pH, extractable P, K and Mg, organic matter (loss on ignition and dumas methodologies), total N, bulk density, penetrometer resistance, visual soil assessment of soil structure (VESS), earthworm numbers, respiration (CO_2-burst), microbial biomass carbon (MBC), potentially mineralisable N (PMN), nematodes, microarthropods and DNA measures of pathogens (Project 05) and beneficial biology (Projects 05 and 06). The assessments will be evaluated in relation to any differences in crop health and productivity.

The Gleadthorpe experimental site was sampled in September 2019. This site investigates the impact of long-term organic material additions (at recommended rates) on soil and crop quality in an arable rotation (cereals and oilseeds) and was previously studied as part of the Defra Soil-QC experimental programme (SP0530). Established in 1991 on a loamy sand (‘Cuckney’ Soil Series; 6% clay), treatments include annual applications of broiler litter (20 years of additions), cattle farmyard manure (FYM), cattle slurry, and green compost (8 years of additions), compared to a control treatment receiving inorganic fertiliser only. Repeated applications of FYM and green compost increased soil organic matter content (SOM), nutrient status and pH (P<0.05). Increases in SOM were not significant following the broiler litter and slurry applications, although nutrient status was improved. Visual Evaluation of Soil Structure (VESS) showed some evidence of structural degradation (capping and compaction) where SOM was low on the control treatment (VESS limiting layer score of 3 or moderate structural condition, compared to a score of 2 where organic materials had been applied – good structural condition). Earthworm numbers were low/depleted across the experimental site which was probably a reflection of the light textured (6% clay) soil and plough-based method of crop establishment. Other soil biological properties – microbial biomass, potentially mineralisable N and CO_2-C respiration burst were numerically higher following all organic material additions, but these differences were not statistically significant. Spring barley yields in 2018 and 2019 tended to be highest following the repeated broiler litter applications (P=0.05, in 2018); a similar pattern was observed in winter wheat at harvest 2020, with yields numerically higher where broiler litter had been applied (although this was not statistically significant). In relation to the soil health scorecard (Figure 1), organic material application scored more favourably than the manufactured fertiliser control, particularly for soil chemical properties (pH, extractable K, Mg, organic matter), although extractable P increased to Index 4.

Treatment	Control	Broiler litter	FYM	Slurry	Green compost
pH	6.8	6.6	7.9	7.4	7.5
SOM (% LOI)	1.9	2.1	2.7	2.2	2.8
Ext P (mg/l)	42	71	53	46	48
Ext K (mg/l)	96	192	326	155	177
Ext Mg (mg/l)	32	60	75	57	62
PMN (mg/kg)	12	26	31	36	35
CO_2-C (mg/kg)	68	85	80	82	77
VESS score (limiting layer)	3	2	2	2	2
Earthworms (No/pit)	0	1	0	1	0

Figure 1. Soil health scorecard for Gleadthorpe organic manure experiment.

The 'Old Rotation' experiment in Woodlands Field at SRUC Craibstone near Aberdeen was sampled in October 2019. This experiment was established in 1922 and investigates the impact of 6 different fertiliser treatments on soil properties and crop performance of a 6 course rotation comprising: 3 year grass/clover ley, spring oats, potatoes, spring barley (undersown with grass/clover). Each crop in the rotation is present every year enabling a comparison of the response of all crop types within the same season. All treatments receive FYM once every six years. The other treatments are NPK (P as superphosphate), NPK (P as rock phosphate), NK, NP and PK. Soil health assessments were undertaken following 4 crops (3rd year ley, spring oats, potatoes and spring barley) in 2 fertiliser treatments (no mineral fertiliser, NPK with superphosphate). The results show that all fertilised and unfertilised crop types had soil properties that were scored good (green – no action needed) or moderate (amber – monitor) according to the soil health scorecard (Figure 2). As expected, P and K status was higher in the fertilised soils, but long-term fertilisation did not have an effect on SOM, pH or soil structure. Soil organic matter levels were highest for fertilised oats and roots, whereas earthworm numbers were greatest in the unfertilised grass ley and lowest in the root crop. As expected, higher yields were attained with fertiliser application for all crop types (1.2-2.5 times higher with fertilisation), with the greatest increases seen in hay yields.

A further four experimental sites were sampled in autumn 2020: the long-term organic material amendment experiment sites at ADAS Terrington (postponed from autumn 2019) and Harper Adams University (repeat sampling – first sampled in autumn 2017), the tillage experiment (zero till compared to ploughing) at GWCT Loddington (repeat sampling – last sampled autumn 2018) and a drainage experiment at ADAS Boxworth (unimproved compared to improved (moled autumn 2017) drainage); samples are currently being analysed.

Treatment	Pasture (Y3)		Oats		Roots		Barley	
	Control	NPK	Control	NPK	Control	NPK	Control	NPK
pH	6.1	6.3	6.1	6.1	6.0	5.9	6.0	6.0
SOM%	10.0	9.4	10.1	11.0	9.7	11.5	9.8	10.6
Ext. P (mg/l)	3	8	3	8	3	8	3	7
Ext K (mg/l)	50	60	60	98	116	162	68	117
Ext Mg (mg/l)	157	173	108	152	168	148	99	93
PMN (mg/kg)	42	38	44	43	44	45	42	43
CO2-C (mg/kg)	123	117	116	101	125	135	123	126
VESS score	2	3	2	2	1	2	2	2
Earthworms (Number/pit)	18	13	8	6	5	4	5	10

Figure 2. Soil health scorecard for the Old Rotation experiment at Craibstone

Key issues to be addressed in the next year

- Complete analysis of the Terrington, Harper Adams, Loddington and Boxworth experimental sites
- Complete compilation of cross-site databases and use to explore links between soil biology, soil structure and crop productivity.
- Update soil health scorecard as appropriate
- Final reporting

Lead partner	ADAS (Anne Bhogal)
Scientific partners	NIAB, SRUC, Fera, GWCT
Industry partners	NRM

Project title	**Monitoring soil-borne disease (DNA measures)**		
Project number	91140002-05		
Start date	01/04/2017	**End date**	31/12/2021

Project aim and objectives

Project 05 (Fera led) aims to demonstrate the value of robust molecular methods (reviewed in Project 3) to quantify the effects of management on soil health across a range of existing (long-term) trial sites and to better understand the link between soil management approaches and minimisation of soil-borne disease risk. Activities across Projects 4, 5, 6 and 7 aim to explore causal links between management and soil-borne disease control by providing some insight into the relationship between pathogen populations and the diversity and function of the overall soil microbiome.

Specific objectives of this project are to:

1. Validate a toolkit of qPCR assays for quantitative detection of the key intractable soil-borne pathogens in arable and horticultural rotations.
2. Establish relationships between pathogen distribution and concentration in soils and potential for disease development.
3. Evaluate the effects of soil management practices (rotations, amendments and cover crops) on the soil microbiome and survival of specific soil-borne pathogens in relation to overall soil health.
4. Design and demonstrate the benefits of an appropriate soil health testing service for growers and agronomists.
5. Integrate results of molecular testing for soil-borne disease risk with associated chemical and physical data to provide a robust soil health scorecard to enable effective on-farm decision support systems for farmers and agronomists.

Key messages emerging from the project

- Methodology has been optimised for standardised extraction and purification of total soil DNA, detection and quantification of a full range of plant pathogens using qPCR, and metabarcoding of bacterial, fungal and metazoan communities; soil samples from several experimental sites have been analysed using the optimised approaches.
- Soil management practices can have an effect on fungal and bacterial communities.

Summary of results from the reporting year
Soil-borne pathogens The Raspberry and Daffodil field sites (Project 07) have been sampled again in 2020, although they did not show significant disease levels in 2019. The DNA has been extracted from the 2020 soil samples and these DNA samples are awaiting qPCR analyses that have been delayed due to Covid related issues. A series of glasshouse trials have started with the aim of monitoring *Verticillium dahliae* in soils in response to Prestop biocontrol applications in strawberries. This work has been designed to follow on and complement the work at the Raspberry field trial. *Soil health – microbiome analysis* Much of the work on the bacterial and fungal microbiomes is carried out in collaboration with Project 06 and is reported together with the work on the nematode/ invertebrates in Project 06. Optimised procedures for soil DNA extraction, high-throughput sequencing of selected metabarcoding targets and bioinformatic analysis have been selected from a number of different possible approaches. In addition, early qPCR results indicated an increased size of fungal and bacterial populations following FYM applications. These results are being verified and will be extended across all trial sites.

Key issues to be addressed in the next year
• Initial data relating pathogen populations in soil to disease development for different crops and pathogens will be further investigated under glasshouse conditions. Glasshouse trials have begun to monitor *Verticillium dahliae* in soils in response to Prestop applications in strawberries. This is to be completed in March 2021. This work might be expanded and complemented with other pathogens detected in the field trials. • Estimates of total fungal and bacterial DNA, using 16S and ITS qPCR assays, will be conducted on samples from all field trial sites to estimate any effects of soil management and compare molecular results with those obtained from indirect methods for estimation of microbial activity used by ADAS. • DNA samples from the 2020 raspberry and daffodil sites are awaiting qPCR analyses to try to relate qPCR results with disease. • A meeting with the SARDI team in Australia took place online on the 7th of October 2020 to allow us to establish links and to learn how their commercial soil-borne disease testing service based on molecular methods was established and how it operates. Further meetings will follow up in 2021 to learn more about technical aspects and knowledge transfer related to the testing service available in Australia.

Lead partner	Joana Vicente, Fera.
Scientific partners	ADAS, NIAB, SRUC, SARDI
Industry partners	None

Project title	Assessing soil health using DNA		
Project number	91140002-06		
Start date	01/04/2017	End date	31/12/2021

Project aim and objectives
Project 06 will evaluate the use of DNA-based analyses to replace individual tests in an appraisal of overall soil health, with the following specific objectives: 6.1 To short-list targets for analysis for DNA-based approaches (from: molecular biomass; total bacteria and fungi; microbial community structure; functional genes; nematodes; microarthropods; earthworms). 6.2 To compare results from soil extracted DNA with current methods for assessing soil health used on the experimental sites in Project 04 and further evaluate the effects of soil management practices (rotations, amendments and cover crops) on the soil biological community and its function 6.3 To optimise the extraction of environmental DNA (eDNA) from soil. 6.4 To compare of results from soil extracted DNA and eDNA. 6.5 To evaluate whether molecular testing for soil health should be integrated with the soil health scorecard and with pest and pathogen diagnosis to provide information on the soil biological community. Ultimately to enable the further development of effective on-farm decision support systems for farmers and agronomists.

Key messages emerging from the project
Biological diversity of metazoan, bacterial and fungal communities in soils can be estimated by molecular methods and were observed to change according to long term cropping and soil management practices. The soil biological community is incredibly diverse. For example, between 100,000–200,000 DNA sequences were obtained for both bacterial and fungal groups from each soil sample from the Harper Adams trial. Use of the on-line databases has highlighted the large gaps in the records for soil-borne organisms. Although most of these soil micro-organisms can be identified at higher taxonomic levels (e.g. phylum, class or order), fewer can yet be accurately assigned at the levels of family, genus or species and even fewer linked directly to soil function. Analysis of the diversity and function of microbiological communities in soils using statistical diversity tests and taxonomic assignments coupled with the available information about the expected biological functions of known taxonomic groups, can assist the selection of key biological indicators contributing to sustainable soil health, crop quality and productivity.

Summary of results from the reporting year
Soil samples have been collected from various long-term management practice trials established to investigate the effects on crop productivity of soil pH, organic amendments, fertilizer applications and cultivation methods (Table 1). A total of 192 samples (2 kg per plot) from all sites were received for

DNA extraction and metabarcoding analysis at Fera to compare metazoan, bacterial and fungal metabiomes across the various treatments. DNA was extracted from 10g subsamples of homogenised soil using the DNeasy PowerMax Soil Kit (Qiagen, Carlsbad, CA, United States) following the manufacturer's instructions. DNA quality and quantity were standardised using a Nanodrop ND-1000 Spectrophotometer (Thermo Scientific, Wilmington, USA).

Table 1. List of experimental sites treatments and barcodes targeted

Experimental Site	**Treatment variables**	**Barcodes targeted**
Loddington	Tillage	16S + ITS
Craibstone-2018	pH*	16S + ITS + CO1
Norfolk	Cultivation/Sampling season	16S + ITS
Gleadthorpe	Organic matter	16S + ITS + CO1
Cranfield	Soil compaction	16S + ITS
Craibstone-2019	Fertilizer*	16S + ITS
Harper Adams	Organic matter	16S + ITS
Terrington	Organic matter	16S + ITS
Boxworth	Drainage	16S + ITS

* Superimposed across a cropping sequence within a rotation

DNA sequencing was performed using a metabarcoding high-throughput sequencing approach to compare metazoan cytochrome c oxidase subunit (CO1) mitochondrial genes, bacterial 16S rRNA and fungal ITS rRNA regions using an Illumina® MiSeq platform, following a modified Illumina protocol. Bioinformatic analysis compared presence of different species, their relative abundances and estimated diversity in different experimentally modified soil ecosystems. Kruskall Wallis and perMANOVA tests were applied to determine whether certain management practices significantly affected microbiome communities and quantify their effect.

Optimised bioinformatic procedures were used to analyse bacterial, fungal and metazoan diversity from total DNA extracted from the various experimental trials. Of the treatment effects analysed so far, soil pH most affected bacterial and fungal communities. Sampling time (spring or autumn) and the cropping cycle within the rotation were also shown to influence biological diversity. Fertilizer applications had a lesser influence on diversity of the microbiome with some significant effects on specific fungal communities, whereas organic amendments appeared only to significantly affect diversity of metazoan communities.

Further investigation is pending on the effects of soil drainage, organic amendments from additional experimental sites and tillage methods on biological diversity.

Key issues to be addressed in the next year
- To complete the evaluation (effectiveness, convenience and cost) of eDNA extraction in comparison with standard soil DNA extraction methods using the 2019 samples collected from the Gleadthorpe organic materials experiment.   - Further evaluation of the impacts of organic amendments across difference soil types/ sites   - Evaluation of the impacts of drainage and tillage   - To consider how molecular testing for soil health could be integrated with the soil health scorecard and with pest and pathogen diagnosis to provide information on the soil biological community so that value, cost and hence the cost-effectiveness of this approach can be considered as part of the assessment in future years.

Lead partner	Christine Watson, SRUC
Scientific partners	NIAB, ADAS, Fera, University of Lincoln, GWCT
Industry partners	None

GREATSOILS

British Beet BBRO Research Organisation

AHDB

Project title	**Managing soil amendments in horticulture**		
Project number	91140002-07		
Start date	01/08/2017	**End date**	31/12/2021

Project aim and objectives

This project aims to quantify the effects of soil amendments and management on soil health in horticultural production systems. Specifically, the following inter-related objectives seek to gain a better understanding of the soil biology and key soil health metrics that should be recorded by growers in order to be able to manage soils to be good for plant health and development:

1. To identify three fields with a history of fungal and/or oomycete soil-borne diseases in preceding horticultural crops and quantify by qPCR the presence of up to six intractable soil pathogens to include at least one able to cause disease in the following horticultural crop;
2. To benchmark the composition of the soil microbiome to be able to analyse changes in the microbial community over the life of the subsequent crop, including the presence and quantity of any pathogens;
3. To carry out physical, chemical and visual assessments of the field soils in tandem with sampling for molecular assays and seek to determine any relationship between these;
4. To record changes in the soil microbiome over one to three years following the use of soil amendments;
5. To determine any relationship between the microbial population composition and levels of disease in onion, narcissus and raspberry as example horticultural crops;
6. To carry out knowledge exchange with growers on the usefulness of the various soil analytical techniques used in the Project for the assessment of soil health / soil disease suppression / pathogen levels of concern.

Key messages emerging from the project

Growers are aware that pathogens such as Verticillium, Fusarium and Phytophthora persist in soils, and that rotations cannot always reduce the disease risk. Soil sterilisation has been employed, particularly in fruit growing, based on the results of soil sampling for *Verticillium dahliae* microsclerotia. Fungicides have also been used, but legislation is removing these options and there is a need for other ways to improve soil and plant health. In addition, relatively new molecular methods of quantifying bacteria and fungi in soil (provided from within Project 05) have opened up the possibility of improving understanding of how pathogen levels in the soil may correlate with disease severities, the other organisms present and other measures of soil health. Project 07 has evaluated the incorporation of organic matter from a cover crop and/or green compost ahead of onions, pig manure or green compost ahead of Narcissus and fibre digestate (crop-based) ahead of raspberries, evaluating impacts on crop vigour and disease. Beneficial fungi, either at planting of the onion crop (mycorrhizal inoculation) or as a drench to the raspberries (‘Prestop’ - *Gliocladium catenulatum)* were also evaluated. Crop health measurements have now been compared in treated and untreated Onion, Narcissus and Raspberry crops, and these will be evaluated alongside the other measurements investigated for objectives 2,3,4 and 5 in order to able to provide messages to growers encompassing a broad approach to soil health.

GREATSOILS

British Beet BBRO Research Organisation   AHDB

Summary of results from the reporting year

Soil sampling for physical and chemical properties and earthworms were carried out in 2017 at the selection of trial sites. Free-living nematode species and *Verticillium dahliae* microsclerotia were quantified, and molecular testing (qPCR) recorded the presence of crop pathogens. Further soil samples were taken just prior to the establishment of Raspberry and Narcissus in 2018 and of Onions in 2019. Soil health scorecard assessments (using the on-farm protocol nutrient concentrations, organic matter, PMN, Visual Assessment of Soil Structure and earthworm count) were completed in autumn/winter 2020 and will be summarised in the final report.

Raspberry cv. Maravilla polythene tunnel crop in How's Field, Tunstead, Norfolk:
The field had a high 41.6 *Verticillium dahliae* microsclerotia / g soil pre-planting. Four treatments in plots of 8 m of row were randomised in six replicate blocks: control (no amendment), anaerobic digestate (50 t/ha), biofungicide alone, and digestate plus biofungicide. Anaerobic digestate was incorporated prior to planting raspberry modules in spring 2018. Two plots per replicate were left untreated at this time, but subsequently plants in one treated and one untreated plot per replicate received a standard 0.5% concentration drench of the biofungicide Prestop (*Gliocladium catenulatum*). Prestop was given at 10% of root ball volume in May, June and October in 2018 and 2019, and in 2020 a fortnight apart in only May and June. No phytotoxicity was seen from any treatment.

The fruiting canes assessed in 2020 were produced from the stool in the Spring following post-harvest fruiting cane removal in Autumn 2019 resulting in later fruiting than in 2019. Assessments were made of cane vigour and wilting in May, June, September and October 2020. As in previous years, no consistent differences in vigour were seen between treatments and no Verticillium wilt developed.

The fruit was harvested regularly and weighed by the farm staff across all plots. During peak harvest-time, the ten plants in the centre of each plot were picked on 9 September 2020 for grading and weighing. No significant differences between treatments in either Class 1 fruit weight (mean 778 g / plot) or unmarketable fruit (210 g / plot) or berry weight (mean 6.3 g) was shown between Treatments.

Soil samples were taken for qPCR from around the ten central plants of each plot in June 2020 before the second Prestop drench but, as more than 50 g soil was required for multiple extractions, bigger samples were taken on 21 October. Visual soil assessment, earthworm count and penetrometer resistance were assessed on 21 October, together with sampling for nematodes and *V. dahliae* in replicates 1, 3 and 5.

***Narcissus cv. Carlton in Orange Field, Terrington St Clements, Norfolk*:**
Fusarium oxysporum, the cause of wilting in Narcissus, was not found in the soil using qPCR pre-planting. However, half the bulbs in a sample taken at planting in August 2018 had Fusarium. There were four treatments: untreated control, pig FYM, green compost and a biological control agent (mycorrhizal inoculation). Prior to bulb planting, either pig manure (35 t/ha) or green compost (50 t/ha) was incorporated in two treatments and two left untreated, with mycorrhiza granules added at planting

to one of these. Two central rows per plot were assessed, in five replicate blocks, with 1700 bulbs / 10 m plot.

The Narcissus crop was grown for a second year to harvest for bulbs. In April 2020 the population of free-living nematodes and the *V. dahliae* microsclerotia was re-assessed in replicates 1, 3 and 5 and soil taken for qPCR from all plots. Further qPCR samples were taken just before the bulbs were harvested on 4 June 2020. Topsoil nutrient and organic matter concentrations were determined on 8 July 2020 before the farmer applied biosolids prior to cultivation. VESS, earthworm counts and penetration resistance measurements were undertaken on the same three replicates on 26 August 2020. These results will be presented in the Final report.

On 20 February 2020 flowerbud stems were counted and there were significantly more (P<0.05) in the mycorrhiza treated plots (65.9 /m) than the untreated (44.0 /m) and FYM treated (35.0 /m). However, the mycorrhiza treated plots were together in one half of the field and adjacent plots of the other treatments also had high flowerbud stem counts. Re-analysis allowing for this trend resulted in a loss of significant treatment difference. Yellowing was assessed as it can be a symptom of Fusarium infection, but by 3 April 2020 there was no significant difference between the treatments, ranging from 4.6% of foliage yellowing (untreated) to 11.4% (mycorrhiza).

The bulbs were harvested from 1 m row lengths at four positions per plot on 4 June 2020, graded and weighed by nose size and examined for externally visible Fusarium. There was no statistical difference in the number of healthy bulbs, with a range from 52 to 77 /m. The bulbs with two or three noses in the mycorrhiza plots were, however, significantly lighter (P<0.05) than for the other treatments. There was no significant difference in the number of bulbs with Fusarium, with a mean 5.6 bulbs visibly infested /m, and the incidence of Fusarium ranged, without significant difference, from 6.9% to 10.0% of bulbs across the treatments. Thirty bulbs each from an untreated and mycorrhizal treated plot were sent to the laboratory of the suppliers of the mycorrhizal product and they found that an average of 6.5% and 30% of the bulb root areas had mycorrhiza, respectively. When these bulbs were cut open to see Fusarium basal rot, 23.3% of untreated and 6.7% of the mycorrhiza treated were affected.

Brown onion cv. Rumba in Claypit Field, Shefford, Bedfordshire

A field was selected with a known history of *Fusarium oxysporum* f. sp. *cepae* onion Fusarium basal rot, and qPCR of the sandy loam soil carried out before onion planting showed 438.6 pg/g *F. oxysporum.* The experiment then set up had three treatments and untreated plots randomised in six replicate blocks. Before planting, three strips of a commercial cover crop mixture of rye, vetch and Phacelia were direct drilled on 31 August 2018, but dry weather caused poor establishment. On 7 March 2019, the equivalent of 30t/ha of green compost (PAS 100 garden waste 0-30 mm) was spread on half of the cover cropped and half of the uncropped plots, giving four treatments: untreated control, cover crop, compost, cover crop + compost. The onion sets planted in April 2019 in 11m x 1.83m plots were free of Fusarium. Final assessment of the foliage in August 2019 (commercial harvest time) showed a mean 89.5% of the crop was unmarketable, with varying extents of leaf tip yellowing corresponding with a severity of bulb internal browning and the presence of purple dry roots. There was no significant difference between the treatments: untreated plots had 13.2% marketable onions, plots cover cropped and receiving compost were 10.3% marketable, those only cover cropped were 9.9% marketable, and plots with compost alone were 8.7% marketable. Soil sampled for free-living nematodes in November 2019 showed the presence of various cereal and potato pests, but not of *Ditylenchus* sp. the stem nematode of onions which could otherwise have added to the foliar yellowing and bulb discolouration attributed to Fusarium. Soil was not sampled at this time for *V. dahliae* as it is not an onion pathogen, although Harris tests had shown a high microsclerotia density pre-planting.

Key issues to be addressed in the next year

- In conjunction with the other projects in the partnership, examine the results from the various soil assessment methods and consider how they might indicate differences in soil health, and working with Project 5 determine whether pathogen levels in the soil determined by qPCR pre- or post-cropping can be related to crop disease incidence or severity.

Lead partner	ADAS
Scientific partners	Fera
Industry partners	Place UK, PS and JE Ward, F.B. Parrish & Son Ltd.

Project title	**On-farm monitoring of soil health**		
Project number	91140002-09		
Start date	01/08/2017	**End date**	31/12/2021

Project aim and objectives

In this project we will establish 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). We will ensure that the innovation groups include farmers with sugar beet, potatoes and or horticulture in their rotations, as well as reduced / zero-till cereal/oilseed rotations and grass-based systems. The overall aim of WP3, Project 09 is 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 collate data on impacts of crop yield/ quality and measurements of soil health using paired field comparisons/ split field treatments.

The specific objectives project are to:

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)
2. Support the use of a soil health scorecard approach (developed in WP1, Project 02) 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 and their extent over 3 cropping years within on-farm rotations
3. Work with at least one farmer in each group to establish on-farm trials that compare / contrast different management approaches alongside their normal practices (e.g. split field experiment) that dovetail and/or extend the range of treatments studied in the trials in WP2 (Project 04 and 07) and collate data on impacts of changed management on soil biology and health
4. Collate the data from all the farmer-research innovation groups and test and develop the descriptive model developed in WP1 (Project 01). Case studies of the innovative practices (both written and in video form) will be developed together with the farmer groups. Outputs from the model, these on-farm studies and the outputs of the research projects in WP2 will be used to develop a range of appropriate KE materials as part of Project 10.

Key messages emerging from the project

The presentation of data in the soil health scorecard format is valued by the farmer groups, and when used more widely within the Monitor Farm programme, and has supported interesting discussions about different management systems and their impact on soil health and wider production and environmental outcomes.

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.

Linking the soil health scorecard and the management impacts tool will allow farmers to use the information from the soil health scorecard to identify the most relevant soil-improving practices for their soil and farming system.

Summary of results from the reporting year

In total, 42 soil health assessments had been made by the SBSH farmer innovation groups on 20 farms between early October and mid-December 2019; this was 75% of the samples identified and promised by the farmers (usually as paired on-farm comparisons). Where the expected samples were not taken, it was usually saturated soil conditions that limited access for sampling. In spring 2020, these data were compiled into the full scorecard format. These data have been used for some preliminary review of the "traffic lights" used for benchmarking within the Soil Health Scorecard. For example, low earthworm numbers are seen in most light (sandy) soils (Figure 3, as also seen in the Research Site at Gleadthorpe (Project 04). This has 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; 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. In addition, ORC carried out sampling on 19 sites (in comparator groups) monitored in the Livewheat project. ADAS have also re-sampled the long-term CTF fields at Barfoots (originally sampled as part of the PF Hort project).

The scorecard approach has also been welcomed more widely as a KE tool for reporting and supporting discussion of soil health. Work began with the C&O Monitor Farms in 2019, this has been rolled out further in 2020, and there has also been a pilot for B&L Monitor Farms and ongoing sampling by the Farmer Facilitation Groups working with the Partnership. This has added a further 60 Soil Health Scorecards to the database in 2020. Good links are also being established between Monitor Farms and SBSH groups in NE, NW England and East Midlands. Full data analysis is awaiting the compilation of the full dataset together with the 2020 samples and the wider sample set collected as part of the Monitor Farm programme and by other Farmer facilitation groups working together with the SBSH Partnership.

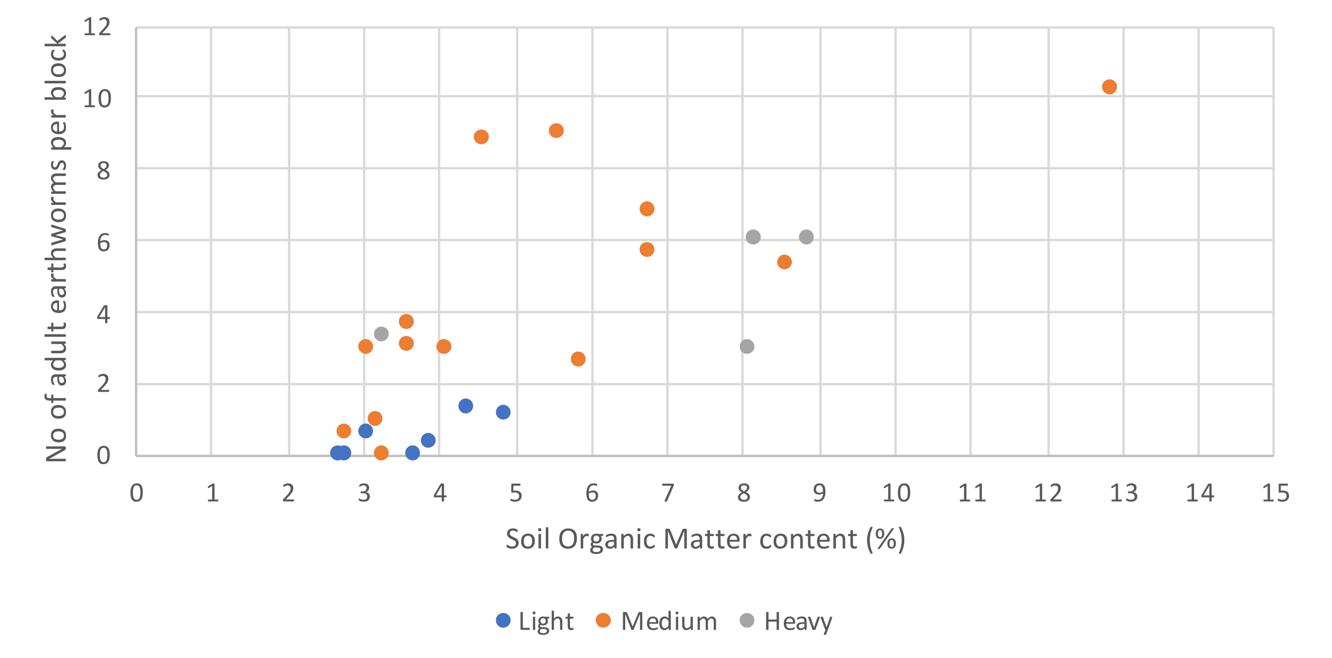


Figure 3. Earthworm numbers in cropping systems – samples collected in Autumn 2019 from the SBSH farmer innovation groups

Soil health scorecard data are now being collated across all sites and seasons. The harvest 2020 data has been requested for all 2019 sampling sites. Where possible, this is now being combined with the more extensive data collection for the rotation associated with Project 13. Full data analysis will then follow. In addition, once the data are collated, we will sense check all the traffic lights again, before developing the final guidance for collection and interpretation of the Soil Health scorecard.

Evaluation and update of management wheel using both research sites and farmer sites is scheduled alongside the data collation in spring 2021. The Management Tool has had changes made to include effects of i) increasing pH and ii) providing field drainage. Effects on earthworms have been presented as a separate outcome and are no longer part of the general soil biology outcome. Creating outcomes for some key combined management changes was tried but the overall outcomes became too similar to be of robust use for management.

The farmer group meetings planned for Spring 2021 are currently under review in the light of changing Covid-19 restriction/lockdown. The shape of these meetings is therefore not yet clear, and we are also looking to seize opportunities to hold shared meetings locally to facilitate knowledge exchange with AHDB Monitor Farms including cross-sector conversations. We will bring the farmers from the groups together (virtually if necessary) to share their experiences and provide a farmer review step in the development of the project KE messages.

Plans are being established for sampling in autumn 2021 – this will largely focus on revisiting some sites sampled in 2018, where changes in management were underway.

Key issues to be addressed in the next year
• Collation of Soil Health Scorecards across sites and seasons • Review benchmarks and develop guidance for on-farm use of the Soil Health Scorecards to inform management. • Evaluation and update of the management impacts tool using farmer sites and management information • On-going work with the farmer groups will review the findings so far, develop case study outputs and review the guidance documents that will be developed for use of the Soil Health Scorecard to ensure accessibility. • Continue to contribute to work that seeks to promote co-ordination and discussion amongst the providers and users of soil health data so that improved understanding rather than confusion results for farmers and growers.

Lead partner	NIAB
Scientific partners	ADAS, SRUC, GWCT, ORC
Industry partners	NRM, Frontier, LEAF, Innovation for Agriculture, BASF, Wye & Usk Rivers' Trust

Project title	Knowledge exchange		
Project number	91140002-10		
Start date	01/01/2017	End date	31/12/2021

Project aim and objectives

Within the Soil Health Research Partnership, this project aims to develop and disseminate co-designed KE outputs resulting from the knowledge gained mainly through the projects of the Soil Biology and Soil Health Research Partnership. We are also working to link and create a coherent set of inter-locking messages with the Research Partnership for the "Management of Rotations, Soil Structure and Water". The project will arrange a series of on-farm events to share knowledge of emerging findings throughout the partnership and allow agri-business to provide inputs as critical friends to the partnership. All the outputs will be designed to be easily accessed, understood and implemented by farmers to aid them in the improved management of soil health.

The specific objectives for this KE project are to

1. Provide base-line understanding of soil biology and monitoring and management of soil health on farm at KE events in Year 1 of the project using workshops and demonstrations.
2. Use farmer-researcher interaction to co-design farmer-friendly KE material that supports the development of improved understanding of soil biology and practical advice relating to the monitoring and management of soil health.
3. Produce KE materials in formats influenced by co-design with famers to be made available through KE events within this project and as legacy KE through AHDB and BBRO media outlets and by other agreed means.
4. Present research outcomes demonstrating increasing understanding of soil biology, the use of the soil health scorecard and how management on farm affects soil health through workshops and demonstrations in Years 3 and 5 of the project.

Project activity

The SBSH programme was in its fourth year and as a result, no major KE activities within the SBSH Partnership were planned in 2020 However, the SBSH Partnership provided a significant input to the AHDB Cereals and Oilseeds Monitor Farm programme over the year.

The Partnership has developed the text for further Research Case studies

- Testing the effects of organic material additions on soil health. Long-term experimentation at Gleadthorpe
- Testing the long-term effects of fertilisation on soil health. Woodlands Field, Rotation Experiment, Craibstone.

These have not yet been published as AHDB are re-evaluating the formats and structure of dissemination in this topic area, hence we are working with AHDB as needed to update existing materials and to develop new ones as needed.

Preparation work is underway to develop the final years KE programme and to build strong links with the AHDB KE teams to ensure the project impact into the future.

GREATSOILS

Partnership projects featured in the following in the past year	
Contributions to other events	
Oxford Farming Conference – UKRI Innovation Hub (E Stockdale, NIAB) Farmer/industry workshop	07 January 2020
Oxford Real Farming Conference – soil seminar (E Stockdale, NIAB) Farmer seminar	08 January 2020
Agronomy North West – Soil Health (A. Bhogal, ADAS) Industry conference	28 January 2020
AHDB Agronomy Roadshow in Stirling, Aberdeen and Inverness (Joanna Cloy/Paul Hargreaves, SRUC) Farmer, consultant and industry event	21 to 23 January 2020
Demonstration for Glasgow University undergraduates (Paul Hargreaves, SRUC) Workshop	3 February 2020
Top fruit grower group – Sainsburys (E Stockdale, NIAB) Farm walk and workshop	10 February 2020
Farmers meeting in Grantown-on-Spey (Paul Hargreaves, SRUC) Farmer/consultant workshop	13 February 2020
AHDB Monitor Farm – Pembrokeshire – Soil Health (E Stockdale, NIAB) Farm walk and workshop	27 February 2020
AHDB Strategic Farm Week. 'Soils Masterclass' – assessing soil structure and earthworm populations. (A. Bhogal, ADAS)	03 June 2020
Hampshire and Isle of Wight Wildlife Trust – Farmer /catchment meeting – Soil health review; (E Stockdale, NIAB) Small-group workshops	07 July 2020
AHDB - Grasscheck series – Grassland soils – knowing what you've got and how to improve it; (E Stockdale, NIAB) Webinar	17 September 2020
Guest lecture SRUC controlled traffic and soil health (Paul Hargreaves, SRUC)	19 November 2020
FAS (Farm Advisory Service) Scotland - Soil Health and Organic Farming Webinar (Paul Hargreaves, SRUC)	17 November 2020
Controlled traffic and soil health Guest lecture for Agricultural students at SRUC (Paul Hargreaves, SRUC)	19 November 2020
AHDB Monitor Farm series with Anglian Water– Exploring soil health at Northampton Monitor Farm; (E Stockdale, NIAB) webinar	24 November 2020
Soil health; Webinar for farmers and advisors, Gotland, Sweden (C Watson, SRUC)	30 November 2020
FAS (Farm Advisory Service) Scotland - Soil Health, biology and compaction; Webinar (Paul Hargreaves, SRUC)	8 December 2020
AHDB Monitor Farm series – Using the Soil Health Scorecard (focussed on the work at Penrith MF); (E Stockdale, NIAB) webinar	14 December 2020

Press articles	
Arable Farmer Article focussing on Project 09	April 2020
Crop Production Magazine	May 2020
Conference presentations, papers or posters	
Soil health and climate change poster presentation 12th Royal Society of Chemistry - Analytical Environmental Chemistry conference (Joanna Cloy, SRUC)	7 December 2020
Scientific papers	
Other	
FAS soil health test video (Joanna Cloy, SRUC)	October 2020
Filming for John Deere video on precision application of slurry and overall soil health (Paul Hargreaves, SRUC)	28 October 2020
Soil health assessment training for consultant at Balbirnie farm (AHDB Strategic farm project) (Joanna Cloy, SRUC)	November 2020

Lead partner	NIAB
Scientific partners	SRUC, ADAS, Fera, GWCT
Industry partners	NRM, Frontier, LEAF, Innovation for Agriculture, BASF, Wye & Usk Rivers' Trust

Project title	Testing soil health and resilience using soil respiration activity		
Project number	91140002-12		
Start date	April 2020	End date	March 2021

Project aim and objectives

The project aims to collect additional information on soil health by expanding measurements on soil metabolic activity and diversity. The objective is to collect data on soil respiration *in situ* and use substrate induced respiration to perform community level physiological profiling (CLPP) giving information on the microbial diversity and activity within the soil. The overall aim will be to make measures of soil health more relevant to farmers, with direct measurements of soil activity, giving indications of soil productivity in terms of nutrient cycling and carbon cycling.

Key messages emerging from the project

Soil greenhouse gas emissions are often poorly understood. This projected has highlighted that they can change seasonally due to management and environmental change. A better understanding of how management affects soil gas fluxes across the seasons can help understand the overall effect of management and soil health on greenhouse gas emissions.

Measurements of microbial metabolic activity and diversity using the Microresp© analysis has highlighted that cultivation can have a huge impact on the microbial community. Microbial activity was halved in the ploughed plots when measured in Spring after cultivation. Further analysis will aim to see if this is linked with the other soil health indicators measured in these plots.

Summary of results from the reporting year

A field that had been exclusively no till for seven years had three strips ploughed every year from 2017 to 2020; sampling in 2020 gives us valuable information on the impact of returning to a fully plough-based cultivation system from a no-till system.

Greenhouse gas emissions from the soil have been measured 5 times in the tilled and direct drilled plots. No significant difference was seen in the CO_2 or N_2O soil flux measurements taken, but there was a trend for higher CO_2 in ploughed plots in early Spring, and higher CO_2 released in direct drilled plots from Summer onwards into Autumn. This is presumed to be due to the impact of cultivation in the Spring.

During the Spring Summer and Autumn measurements of greenhouse gas flux, soil was also collected and used for MicroResp© analysis; this uses substrate induced respiration to calculate the activity and diversity of the microbial community within the soil. Microbial activity was halved in the ploughed plots when measured in Spring after cultivation. Initial results suggest that the activity and diversity of the microbial community is higher in the direct drilled plots.

Key issues to be addressed in the next year
• Further analysis will be carried out to see how the GHG emissions and functional diversity data correlate with other soil health measurements taken within these plots. • More detailed analysis of the data is planned with an overall aim to look for links between the soil properties measured, and functional changes in the soil community, leading to a better understanding of how the soil system is changing with treatments.

Lead partner	GWCT (Jenny Bussell)
Scientific partners	
Industry partners	

GREATSOILS

British Beet BBRO Research Organisation AHDB

Project title	Drawing out associations between soil health, crop yield, environment and management – advanced data analysis and statistical modelling		
Project number	91140002-13		
Start date	April 2020	End date	December 2021

Project aim and objectives

This project brings Biomathematics & Statistics Scotland (BioSS) as a research partner alongside the Partnership researchers to deploy advanced data analysis and statistical modelling approaches to explore the associations between soil health indicators, crop yield and investigate the relationships with environmental and management variables.

The objectives are:

1. Develop clear database design for soil health and associated variables arising from a number of different research trials and on-farm monitoring sites, together with robust protocols for data input, data validation and extraction.
2. Carry out data analysis and statistical modelling to:
   a. Identify associations between environmental (crop, soil texture/type and climate) conditions and soil health to crop yield
   b. Identify patterns relating management options to soil health.
   c. Identify how environmental conditions modify the effects of management on soil health.
3. Work with the Partnership project teams to disseminate the key conclusions from the statistical analysis in a clear and accessible manner to end-users.

Key messages emerging from the project

Key messages will emerge in 2021 once the data analysis has begun.

Summary of results from the reporting year

Working with AHDB, it was agreed that the background site/ rotational data would be collated in a format that built from the format developed by the Grower Platform within the Soil and Water Partnership Programme (91140001). This will allow additional value to the analysis and development of summary indices for the complex rotational datasets than can be used alongside the Soil Health Scorecards. BIOSS, NIAB and ADAS have worked together to develop plans for data collation from SBSH project sites. The new simplified Grower Platform format was agreed in early December 2020.

The main data collection phase is now on-going following the autumn drilling window but given the delayed confirmation of the format is not expected to be fully complete before February 2021.

Key issues to be addressed in the next year

- Data analysis and statistical modelling to identify associations between environmental (crop, soil texture/type and climate) conditions and soil health to crop yield;

- Data analysis to identify patterns relating management options (and their combinations) to soil health.
- Dissemination of the key conclusions from the statistical analysis in a clear and accessible manner to end-users.

Lead partner	NIAB
Scientific partners	BIOSS, SRUC
Industry partners	

Project title	Rectifying soil structural damage using vigorous rooting green crops		
Project number	91140002-14		
Start date	October 2020	End date	March 2021

Project aim and objectives

This project will summarise current guidance on how to rectify soil structural damage, including the use of vigorous rooting green crops for this purpose, and provide sign-posting for a farmer/grower using the soil health scorecard on the options available for improving soil physical condition.

Specifically the project aims to:

1. Review the UK evidence (extended to studies undertaken in temperate cropping systems where appropriate) for the use of green crops to repair structural damage following harvesting/trafficking in wet conditions.
2. Summarise the current advice on rectifying soil structural damage (across the range of sectors), outlining the potential options available to farmers and growers and providing sign-posting to existing relevant guidance that is specific to the sector in question.
3. Evaluate and test the soil health scorecard approach at two case study sites where soil structural damage is evident:
    - Wyevale Nurseries Transplant Division (hardy nursery stock)
    - 'SoilCare' project compaction study at GWCT

Key messages emerging from the project

Key messages will emerge in early 2021 from the rapid evidence assessment, advice summary and field data.

Summary of results from the reporting year

1. We have developed a set of research questions and set inclusion and exclusion criteria for the literature searches, which will be limited to UK and other countries with a temperate oceanic climate within the temperate latitude range: ranges (23.55°-66.5° N or S). The first set of searches have been completed and returned 312 research papers. The next steps will be to include/exclude papers based on the title and abstract and to extract the key information using a proforma developed for the project.
2. Current advice on rectifying soil structural damage (across the range of sectors) will be summarised in January and February 2021.
3. Field work to test the soil health scorecard approach at Wyevale Nurseries Transplant Division (Herefordshire) and the *SoilCare* 'compaction' plots at Loddington (Leicestershire) has been completed and data collated for analysis.

Key issues to be addressed in the next year

1. Complete the rapid evidence assessment
2. Complete the advice summary
3. Analyse and interpret data from Wyevale and Loddington

Lead partner	ADAS (Paul Newell Price)
Scientific partners	SRUC, GWCT
Industry partners	Soils will be analysed by NRM laboratories