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Quantifying the effects of management on soil health

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1. Abstract

This project evaluated the effectiveness of using the Soil Health Scorecard which integrates a number of chemical, physical and biological indicators (developed in an earlier Soil Biology and Soil Health Research and Knowledge Exchange (SBSH) Partnership project, Project 2) to give an overview of soil health. The scorecard was used at a number of existing experimental sites where management practices had been implemented that controlled the key drivers of soil biological functioning, specifically: food source (organic matter inputs and crop rotation), air and water supply (tillage and drainage) and soil pH. These sites also provided a test bed for other potential indicators of soil health (not on the scorecard), including more detailed soil biological assessments and the development of molecular based techniques within Projects 5 and 6 of the partnership.

The network of seven experimental sites had known differences in soil organic matter content, pH and drainage status/structure and covered a range of soil and agro-climatic conditions and rotations with grass leys, cereals, sugar beet and potatoes. At each site, crop yield and quality were assessed each year and at least one soil health assessment was undertaken in the autumn between 2017 and 2020. Measurements included: visual evaluation of soil structure (VESS), topsoil pH, extractable P, K & Mg, organic matter, earthworm numbers (the main Soil Health scorecard measures), together with CO_2-C burst, potentially mineralisable N (PMN), microbial biomass carbon (MBC), bulk density and penetrometer resistance.

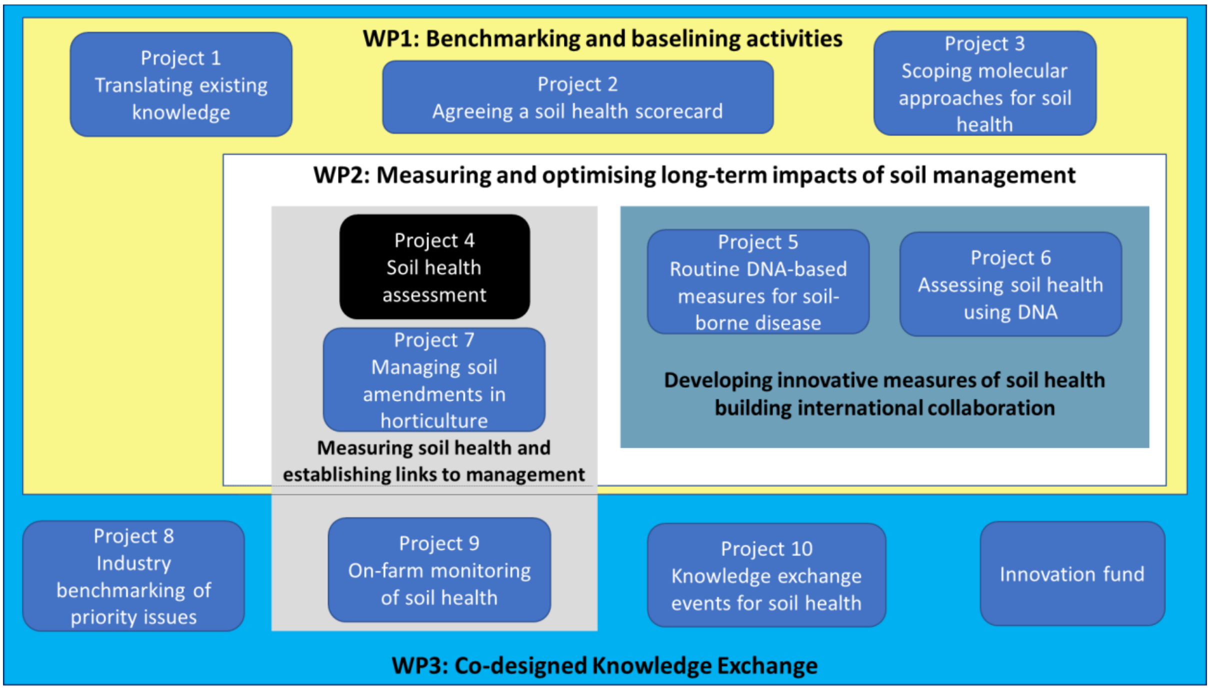
The evaluation showed that the suite of measurements included on the final scorecard (i.e., pH, SOM, Ext. P, K, Mg, VESS, earthworm count, PMN and CO_2-C burst) and their benchmark values were effective at identifying situations where soil health was potentially ‘sub-optimal’, either limiting production and/or increasing the risk of negative impacts on the environment. A positive relationship between grain yield and a number of the soil characteristics included in the Soil Health Scorecard, particularly organic matter and nutrient status, was observed across three long-term sites receiving repeated organic material additions. This confirmed that there is a link between the soil characteristics included in the Soil Health Scorecard and soil function thereby confirming their value as indicators of soil health. Differences between sites were greater than differences between individual management practices at a single site, demonstrating the importance of knowing ‘site’ factors such as soil type (texture), drainage, climatic region and management history (crop rotation), when undertaking soil health assessments. The interpretation of Soil Health Scorecard results from the experimental sites showed the following responses to the different management practices evaluated i.e.:

- Optimising pH to c. 6.5 maximises nutrient availability, biological activity and crop productivity.
- Organic materials (particularly bulky, high dry matter materials) are a valuable source of nutrients and organic matter, with some having value as a liming material, as well as increasing soil biological activity.

- Inclusion of grass leys (for 2-3 years) improves soil organic matter, nutrient status, biology and structure.
- Intensive cultivations (e.g. associated with root crops) reduce soil penetration resistance and bulk density, and result in a decline in earthworm numbers. However, occasional tillage of no-till fields does not necessarily result in a significant decline in soil function.

2. Introduction

This project (Project 4 of the Soil Biology and Soil Health Partnership, SBSH) aimed to quantify the effects of contrasting management practices on soil biology and health in relation to crop yield and quality. It is part of a suite of integrated projects within the Soil Biology and Soil Health Research and Knowledge Exchange 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 for soil health assessment (Project 2) which uses several chemical, physical and biological indicators to provide 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 4 was conducted within Work Package 2 (WP2) of the SBSH Partnership which brings together Projects 4, 5, 6, and 7, and aimed to improve understanding of the role of soil biology in overall soil health, with respect to the ability of soils to support and sustain healthy and productive crops. In particular, WP2 aimed to establish any aspects of soil biology that are key to soil function and explore practical and effective ways to measure and manage biological indicators alongside already established techniques for measuring and monitoring soil physical and chemical properties. The soil health scorecard approach developed was also used in Project 7 (soil amendments in horticultural crops) and Project 9 (on farm monitoring).



Project 4 shown (in black) within the integrated project delivery of the Soil Biology and Soil Health Research and Knowledge Exchange Partnership

2.1. Objectives

The overall aim of Project 4 was 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 were:

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 5 and 6)
6. As part of the whole SBSH 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).

2.2. Background

Sustainable soil management is central to the delivery of economically and environmentally sound, resilient and productive cropping systems. Improving/securing soil ‘health’ has therefore been increasingly discussed, 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 and environmental impacts. Soil physics, chemistry and biology are interlinked, and all play a role in maintaining productive agricultural and horticultural systems. Historically, much of the focus on maintaining soil productivity has been on managing chemical and physical properties rather than soil biology. Soil biological functioning is key to maintaining soil health, as it underpins the majority of processes within the soil system (Kibblewhite *et al.,* 2008). Recent advances in soil analysis are providing new insights into the complexities of the soil food web (Pulleman *et al.,* 2012). However, it is unclear whether the results from these techniques can be used to support the maintenance and enhancement of healthy and productive cropping systems (Thiele-Bruhn *et al.,* 2012).

A number of existing experimental sites were selected to explore the *key drivers* (text in italics) of soil biological functioning and how they can be **managed** (text in bold), notably:

- *Food source*: soil biology ultimately relies on soil organic matter (SOM). SOM is fundamental to the maintenance of soil fertility and function, through the provision of nutrients and energy which drive the biological processes that underpin soil structural development, nutrient and water availability (Loveland & Webb, 2003; Defra, 2009). SOM can be manipulated with **external organic matter inputs** such as farm manures and composts and is also dependent on **crop choice** and **rotation** (residue return, grass, cover crops etc). Whitmore *et al*. (2017) showed that amending soil with organic matter can improve crop yields, particularly in 'poor' years with improvements linked to soil physical condition. However, not all organic materials impact soil health in the same way (Bhogal *et al.,* 2018), with marked differences in soil biological and physical functioning observed in soils that have received repeated compost compared with farmyard manure (FYM) additions.

- *Air and water supply*: the majority of soil organisms need adequate air and water which depends on soil porosity. Compaction reduces porosity, reducing biological activity, restricting root growth and water storage capacity (Batey, 2009). Porosity, air and water supply can be influenced by both **tillage** and **drainage**.
- *Chemical environment*: Soil pH directly affects the composition of the soil microbial community, as well as the availability and partitioning of nutrients. At a national scale pH is a major driver for microbial community structure (Griffiths *et al.,* 2011) and variation due to land management changes the microbial community and the mechanisms underlying nutrient transformations (Baggs *et al.,* 2010; Herold *et al.,* 2012) with links directly to crop yield.

The development of soil 'health' indicators has been the subject of considerable scientific effort (e.g. Ritz *et al.,* 2009; Rickson *et al.,* 2013). However, there is a distinction between methods that improve our understanding of soil processes and functions (research-based indicators) and those which provide a practical assessment of soil condition (such as those on the scorecard). There is a need to 'translate' in-depth assessments of soil functions into simple metrics coupled to practical methods of assessment that farmers can use.

3. Materials and methods

3.1. Experimental sites

A network of seven existing experimental sites with a history of different management practices that have resulted in differences in soil organic matter content, pH and drainage status (i.e. key drivers of soil biological functioning) was established, covering a range of soil and agro-climatic conditions and rotations in Britain (Table 3.1 & Figure 3-1). These sites provided the test bed for the scorecard indicators confirmed from Project 2 (Griffiths *et al.* 2018), and facilities to test and develop new indicators of soil biology including molecular-based techniques (Projects 5 & 6).

Table 3.1 Long term experimental site details

Site	Soil textural group		Annual rainfall (mm)	Crop rotation[2]			
	Group[1]	% clay		2016/17	2017/18	2018/19	2019/20
1. Harper Adams (Shropshire)	Sandy /light	12	690	**G**	WW	Pot	**SBa**
2. Gleadthorpe (Nottinghamshire)		6	577	M	SBa	**SBa**	WW
3. Terrington (Norfolk)	Medium	28	630	WW	WW	SB	**WW**
4. Loddington (Leicestershire)	Heavy	40	650	WOSR	**WW**	WO	**SW**
5. Boxworth (Cambridgeshire)	Heavy	43	550	Set aside	**WB**	SBa	**WB**
6. Craibstone-pH (Aberdeenshire)	Sandy /light	12	850	8 crops present each year[3]			
7. Craibstone-crop				6 crops present each year[3]			

[1] Cross Compliance Group; EA (2008)

[2] Crops in the rotation: SBa = spring barley; WB = winter barley; WOSR = winter oilseed rape; WW = winter wheat; G = grassland; SW = spring wheat POT = potatoes; M = maize; Text in bold and shaded grey indicates the years soil health assessments were made (autumn/post-harvest).

[3] At Craibstone every stage of the crop rotation was present each year (see section 3.1.3 below for details); soil health assessments were undertaken in autumn 2018 for the pH experiment and autumn 2019 for the crop rotation experiment

All sites received applications of available nutrients for optimal crop growth based on recommendations in The Nutrient Management Guide (RB209) or appropriate SRUC Technical Notes (unless otherwise stated in the sections below). Crops were grown according to best farm practice using commercially recommended seed rates, with crop protection products applied according to good agricultural practice to control weeds, pests and diseases, with the aim of growing healthy and productive crops.

3.1.1. Experimental sites exploring food source – external organic matter inputs

Sites 1 – 3 (Table 3.1) were long-term experimental sites testing the effect of repeated organic materials additions on soil quality, that were used in the WRAP/Defra funded DC-*Agri* and Soil*QC* experimental programmes (Bhogal *et al.,* 2009, 2011a&b, 2016, 2018). Soils at Harper Adams were a sandy loam (light) belonging to the Wick soil series, at Gleadthorpe they were a loamy sand/sandy loam (light) of the Cuckney soil series and at Terrington they were a silty clay loam (medium) of the Agney soil series. Soil properties on plots receiving applications of different organic materials were compared with a control treatment that received manufactured fertiliser additions only, with the number of years materials had been applied (up until autumn 2017) varying from 3 to 23 years, depending on the site and material (

Table 3.2). Composts (meeting PAS100 criteria) were supplied from CCS certified sites local to the experimental sites and food-based digestates from BCS certified sites or those meeting PAS110 criteria. Livestock manures were supplied from either the host farm (Harper Adams), or local livestock farms (Terrington, Gleadthorpe). All materials were analysed prior to application for total and readily available N content, dry matter, pH and total P, K, Mg and S, and organic carbon (Table 3.3). There were three replicates of each treatment and organic materials were applied at target rates equivalent to *c.* 250 kg/ha total N (120-250 kg N/ha for slurries and digestates, depending on the total N content and dry matter). Additional manufactured fertiliser N was applied at optimum rates based on information from AHDB's Nutrient Management Guide (RB209) and estimates of manure crop available N supply from MANNER-*NPK* model predictions (Nicholson *et al,* 2012) to ensure that the only difference between treatments was the amount and form of organic matter applied.

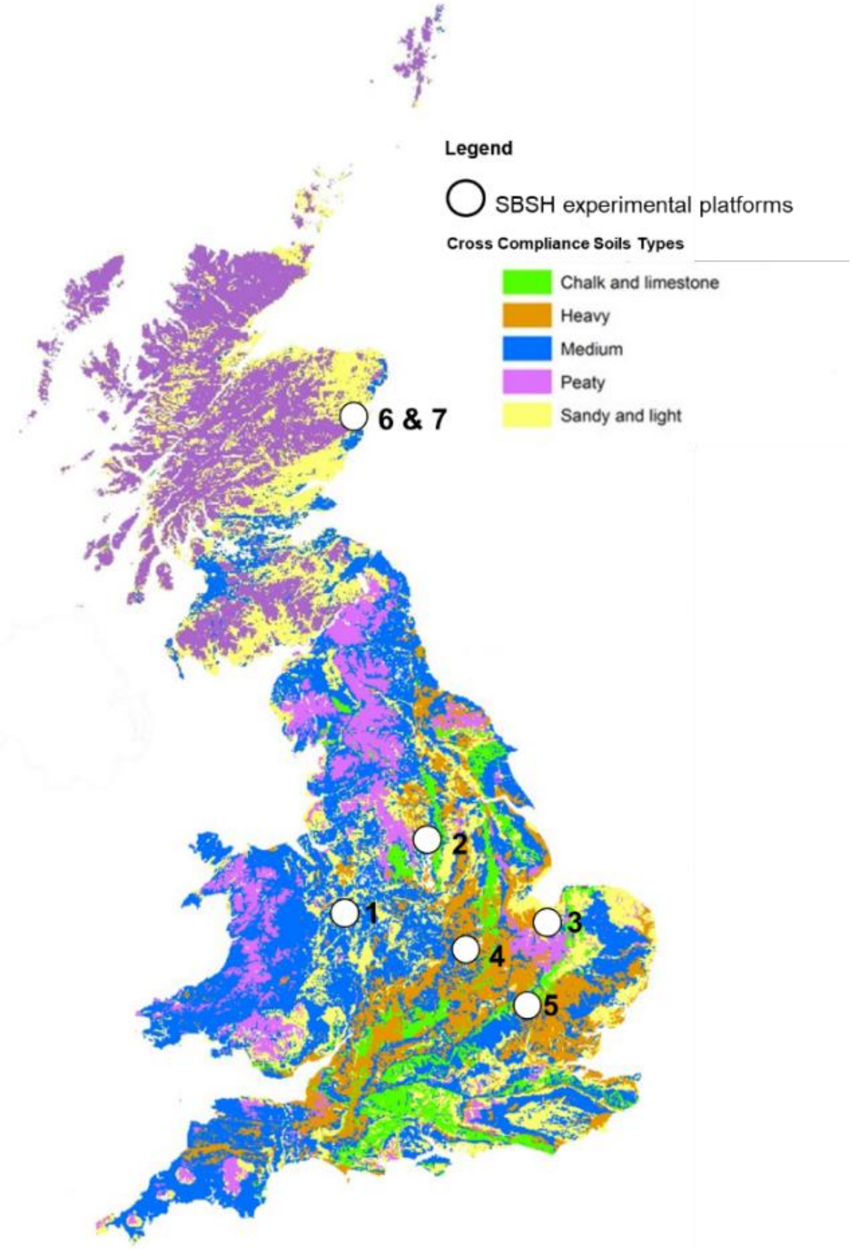


Figure 3-1 Experimental site locations (see Table 3.1 for details)

Table 3.2 Organic material treatments at sites 1-3

Site	Treatment[1]	Date first applied[2]	Number of repeat applications[3]	Organic matter loading (t/ha)[3]
Harper Adams	Cattle FYM	1990	23	129
	Cattle slurry	1990	23	53
	Green compost	2005	13	62
	Green/food compost	2011	7	27
	Food-based digestate	2006	9	7
Gleadthorpe	Broiler litter (10 t/ha)	1993	20	85
	Cattle FYM	2005	8	62
	Cattle slurry	2005	8	20
	Green compost	2005	8	47
Terrington	Pig FYM	1993	23	103
	Pig slurry	1993	23	21
	Green compost	2005	13	69
	Green/food compost	2011	7	31
	Food-based digestate	2011	7	5

[1] At each site there was an un-treated control, which only received recommended rates of manufactured fertiliser

[2] Harvest year

[3] Applications and loadings up until the first soil health assessment (autumn 2017, 2019 and 2020 at Harper Adams, Gleadthorpe and Terrington, respectively).

Table 3.3 Mean organic material analyses, 2017-2020 (standard error in parenthesis)

Organic material characteristic	Units[1]	Cattle/pig FYM (n= 8)	Cattle/pig Slurry (n=8)	Green compost (n=8)	Green/food compost (n=5)	Food-based digesate (n=5)	Broiler litter (n=3)
pH	-	8.1 (0.3)	7.5 (0.1)	7.4 (0.3)	7.8 (0.46)	8.1 (0.1)	7.7 (0.9)
Dry Matter	%	32 (3.0)	5.5 (1.0)	72.7 (8.7)	72.8 (6.5)	4.5 (0.6)	50.2 (2.9)
Total Nitrogen (N)	kg/t fw	6.6 (0.6)	3.1 (0.4)	13.4 (1.3)	13.8 (1.1)	5.2 (0.4)	30.7 (6.6)
Readily Available N (RAN)[3] *% of total Nitrogen*	kg/t fw	0.77 (0.3) *10.1 (3.9)*	1.6 (0.3) *53.6 (8.2)*	1.1 (0.2) *7.8 (1.5)*	0.85 (0.3) *6.1 (1.9)*	3.5 (0.4) *66.6 (4.8)*	10.2 (1.1) *34.3 (2.3)*
Total Phosphate (P_2O_5)	kg/t fw	4.6 (1.0)	1.1 (0.2)	6.4 (0.9)	5.7 (0.6)	2.1 (0.7)	15.5 (0.8)
Total Potash (K_2O)	kg/t fw	8.7 (0.8)	2.6 (0.4)	8.2 (1.1)	8.8 (1.3)	1.7 (0.1)	20.7 (2.0)
Total Magnesium (MgO)	kg/t fw	3.3 (0.7)	0.8 (0.2)	4.4 (0.3)	3.9 (0.2)	0.5 (0.2)	5.3 (0.7)
Total Sulphur (SO_3)	kg/t fw	3.2 (0.5)	0.9 (0.1)	4.4 (0.3)	4.3 (3.7)	1.0 (0.1)	9.7 (0.9)
Organic Carbon	% dm	34.5 (1.7)	34.4 (3.2)	22.7 (2.2)	21.1 (0.5)	31.6 (2.9)	39.6 (1.5)

[1] kg/t fw = kilograms/tonne fresh weight; %dm = percent dry matter; [2] n=number of sites and years measurements were taken over the 3 cropping seasons 2017-2020; materials were not applied at Harper Adams in 2019-2020 due to restrictions on site access as a result of the Covid-19 pandemic. [3] Readily available nitrogen (RAN = ammonium-N & nitrate-N, plus uric acid N for the broiler litter)

Soil health assessments were undertaken in October 2017 (grass ley) and October 2020 (cereal stubble) at Harper Adams, September 2019 (cereal stubble) at Gleadthorpe and September 2020 (cereal stubble) at Terrington.

3.1.2. Experimental sites exploring air and water supply – tillage & drainage status

Site 4 at the Game and Wildlife Conservation Trust (GWCT) Allerton Project in Loddington, Leicestershire (Table 3.1) evaluated the effect of cultivation on soil health in a field with a clay loam soil (heavy) of the Denchworth series that had been no till (direct drilled) for seven years. In autumn 2017, six strips, each 9 metres wide and running the full length of the field were established; three strips were randomly assigned to a 'plough' treatment and three remained 'direct drilled' (no till). A mouldboard plough to a depth of 25 cm was used to establish the plough treatment. The plough treatment was also disked to a depth of 10 cm (Väderstad Carrier) twice every Autumn. In contrast, the direct drill treatment received only a straw rake before drilling. The field was drilled (using an Eco M, Dale drill) with winter wheat in 2017, oats in 2018 and spring wheat in 2019 and soil health assessments were undertaken in autumn 2018 after one year of treatment, then again in autumn 2020, after three years of annual ploughing, and ten years of continuous direct drill.

Site 5 at ADAS Boxworth in Cambridgeshire (Table 3.1) was previously used for the Defra funded 'Cracking clays' project (Defra WQ0118 & AC0111) and comprised 27 arable plots (12m x 48m) on clay soils (heavy) of the Hanslope Association. Each plot is drained with lateral drains at 24 m spacing and 90 cm depth, with gravel backfill to within 30 cm of the surface. The site requires secondary drainage (mole drainage) at 50 cm depth and 2 m spacing for the drainage system to function effectively. As mole drainage was last carried out in 2007 (i.e. 10 years before the start pf the study), the site provided the opportunity to evaluate the effect of drainage improvement on soil health. In August 2017, 3 replicate plots were mole-drained, setting the mole at 55cm depth with a 2 m spacing (giving 6 mole channels across the 12m plot width). These plots were then compared with 3 replicate plots that were not mole-drained, with soil health assessments undertaken in autumn 2020 (3 years after drainage improvement).

3.1.3. Experimental sites exploring crop rotation and chemical environment (pH & nutrient status)

Sites 6 and 7 were in the same field (Woodlands field) at SRUC Craibstone near Aberdeen on a sandy loam (light) of the Countesswells series.

The pH trial (site 6; Table 3.1) was established in 1961 and comprises an eight course rotation, with all eight crops in the rotation grown each year viz. hay (grass/white clover), pasture, pasture, winter wheat, potatoes, spring barley, swedes, spring oats undersown with grass/white clover. (Walker *et al*. 2015). Superimposed across all of the crops are seven different target pH treatments, starting at approximately pH 4.5 going up to pH 7.5, in 0.5 increments (Figure 3-2). The pH adjustments are based on regular soil analysis, with lime used to raise the pH and ferric sulphate to reduce the pH. All pH treatments receive farmyard manure once every eight years, ahead of the potato crop, with recommended rates of manufactured fertiliser applied according to the specific crop requirements.

Soil health assessments were undertaken in October 2018 from four crops (2nd year ley, following winter wheat, potatoes and spring oats) at four pH levels (4.5, 6.0, 6.5 and 7.5), with 8 rotational cycles prior to this sampling (i.e. each crop had been on the same plots 8 times since the start of the experiment). As there was no replication of the treatment plots, ‘pseudo replicates’ were created by splitting the plots into 3 discrete sampling areas, so that each assessment was repeated 3 times within the same plot.

Figure 3-2 Aerial image of the Woodlands field trials at SRUC Craibstone: Left: Long-term pH experiment; Right: Long-term crop rotation experiment. Crop rotation on the pH trial: 3 year grass-clover ley (G1-3), winter wheat (WW), potatoes (Pot), spring barley (SB), swedes (Sw), spring oats undersown with grass-clover (Oat). Crop rotation on the rotation trial: 3 year grass-clover ley (G1-3), spring oats (oat), potatoes (pot), spring barley undersown with grass-clover (SB)

The crop rotation trial (site 7) in Woodlands field was established in 1922 and investigates the impact of 6 different fertiliser treatments on soil properties and the performance of 4 crops in rotation: 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 farmyard manure once every six years, ahead of the potato crop. The other treatments are NPK (P as superphosphate), NPK (P as rock phosphate), NK, NP and PK, all at recommended rates for the relevant crop with an untreated control (Figure 3-1). Soil health assessments were undertaken in October 2019 from 4 crops (3rd year ley, spring oats, potatoes and spring barley) in two fertiliser treatments (no mineral fertiliser and NPK with superphosphate). As there was no replication of the treatment plots, ‘pseudo replicates’ were created by splitting the plots into 3 discrete sampling areas, so that each assessment was repeated 3 times within the same plot.

3.2. Soil health assessments

The following soil health parameters were assessed at each of the sites (with sampling staggered across the lifetime of the project; Table 3.1): visual evaluation of soil structure (VESS), topsoil pH, extractable P, K & Mg, organic matter, earthworm numbers (the main Soil Health scorecard measures), together with CO_2-C burst, potentially mineralisable N (PMN), microbial biomass carbon

(MBC), bulk density and penetrometer resistance (Table 3.4). Soil chemical and microbiological assessments were undertaken on a single representative topsoil sample per replicate plot at each site, taken from 0-15cm. In addition, samples for nematode community analysis (representative soil sample, with nematodes extracted by washing and sieving), mesofauna (intact cores with mesofauna extracted using Tullgren funnels) and molecular analysis of the soil microbial community and mesofauna (DNA extraction from a representative soil sample) were also taken and the results are reported in Projects 5 and 6.

Table 3.4 Soil health assessment methodologies

Soil property	Method
Chemical:	
Soil organic matter (SOM)	Loss on Ignition (LOI) (MAFF, 1986)
pH	Water (MAFF, 1986)
Extractable Phosphorus (P)	Olsen (MAFF, 1986); Modified Morgan's (SAC, 2010)
Extractable Potassium (K), Magnesium (Mg)	Ammonium nitrate (MAFF, 1986)
Biological:	
Microbial biomass C (MBC)	Chloroform-extraction (Brookes *et al*., 1985). Correction factor = 2.22 (Wu *et al.,* 1990)
CO_2-C burst	CO_2 'burst' (Franzluebbers *et al*., 2000; Haney *et al.,* 2008 a,b)
Potentially Mineralisable Nitrogen (PMN)	Anaerobic incubation (Keeney, 1982)
Earthworms	Hand-sorting the cube of soil used for the VESS assessments (3 assessments per plot) counting all worms retrieved in a 5 minute time period (Schmidt, 2001), identified to: adult anecic, endogeic & epigeic species and juveniles. Results tables report total number of adults & juveniles collected.
Physical:	
Visual Evaluation of Soil Structure (VESS)	Three assessments per plot to 25 cm depth (Guimarães *et al*., 2011). Results tables report the limiting layer score (i.e. maximum score recorded).
Bulk Density	Three intact soil cores taken at 5-10cm depth from each replicate plot (MAFF, 1982)
Penetration Resistance	Ten penetrologger readings to 45cm depth per replicate plot, recording resistances every 2-5cm depth (MAFF, 1982); Results tables report the maximum resistance to 30cm depth.

3.3. Crop performance

In each harvest year at each site, crop yields and quality were measured at harvest on each treatment. For the cereal crops, yields were quantified using plot combines (except at Loddington, where a commercial combine was used on the field-scale treatment strips) and grain samples were analysed for total N, P, K and Mg. Where root crops were grown (potatoes, sugar beet), yield and quality assessments were assessed on the marketable parts of the crop and quality assessments included sugar beet sugar & amino N content, and potato skin set and damage (wireworm, scab and black dot).

3.4. Data analysis

At each experimental site, treatment effects on soil and crop properties were evaluated using either conventional analysis of variance (ANOVA) where there were 3 or more replicates (sites 1-3) or ‘pseudo’ replicates (sites 6 & 7), with comparison of P-values. A separate ANOVA was carried out at each site. Where there were only two treatments (sites 4 & 5), a t-test was used.

As sites 1-3 had common organic material treatments (control, FYM, slurry and green compost) a cross-site analysis of variance was carried out on all soil and crop properties measured (using Genstat version 12; VSN International Ltd, 2010). Where differences between organic material treatments were statistically significant, relationships between these soil properties and cereal grain yields were explored further using regression. Relationships between the different microbial indicators of soil health (PMN, CO_2-C burst and MBC) together with estimates of bacterial and fungal biomass from the qPCR analysis of extracted DNA in Project 5 (measured at all sites, except Harper Adams in 2017), were also explored using correlation and regression analysis.

4. Results

4.1. The Soil Health scorecard

The scorecard approach developed within project 2 of the SBSH partnership (Griffiths *et al.,* 2018) brings together information on soil chemical, physical and biological properties using “traffic light” coding to identify the properties that may pose a potential risk to crop productivity or risk of off-site environmental impact, 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). Griffiths *et al.* (2018) also presented 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 (Bhogal *et al.* 2020) evaluated two alternative methods of measuring microbial biomass (potentially mineralisable N – PMN and CO_2-C burst) and provided 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 projects 2 and 11 of the partnership, and finalised in the SBSH ‘Benchmarking tables’ (see Project 9 report) where:

🟥 Investigate

🟨 Review

🟩 Continue rotational monitoring

During the course of the project, it was found that penetration resistance data were highly dependent on soil water content at the time of sampling and as a result the measure was not considered robust enough for comparisons and benchmarking between sites. Assessment of bulk density requires collection of intact cores, drying and weighing facilities and consequently it is not well suited to routine use on-farm. However, as these indicators were measured at all the long-term experimental sites, they have been included in the results sections below to provide more detailed information on soil physical condition.

4.2. Effect of external organic matter inputs on soil health and crop performance

4.2.1. Soil health scorecard at Harper Adams

Soil health assessments were undertaken at Harper Adams in October 2017 at the end of a 2 year grass/clover ley (just prior to destruction of the ley for the following winter wheat crop; Table 4.1a), and then repeated in October 2020 in spring barley stubble (Table 4.1b), following 3 years of arable cropping, including potatoes (in 2019).

Table 4.1 Soil health scorecards (and additional measured attributes) following repeated organic material additions at Harper Adams.

a) Grass/clover ley (2017): 7 - 23 years of repeated additions; treatment means (n=3)

Attribute[1]	Control	FYM (23yrs)	Slurry (23 yrs)	Green compost (13 yrs)	Green/food compost (7 yrs)	Food-based digestate (9 yrs)
SOM (%)**	3.0	4.1	3.6	4.0	3.7	3.4
pH **	6.4	7.0	6.4	7.0	6.2	6.5
Ext. P (mg/l)** [Index]	56 [4]	73 [5]	53 [4]	60 [4]	59 [4]	65 [4]
Ext. K (mg/l)** [Index]	80 [1]	311 [3]	194 [2+]	187 [2+]	140 [2-]	167 [2-]
Ext. Mg (mg/l)** [Index]	44 [1]	87 [2]	75 [2]	63 [2]	66 [2]	48 [1]
VESS score	2	2	2	1	2	2
Earthworms (No/pit)	11	13	9	11	9	13
PMN (mg/kg)**	23	90	24	43	38	43
CO_2-C burst(mg/kg)	198	228	247	222	219	228
MBC (mg/kg)[2]	350	393	315	317	334	345
Bulk density (g/cm^3)[2]	1.40	1.34	1.43	1.29	1.46	1.43
Penetration resistance (MPa)[2]	4.5	4.2	4.6	4.2	4.5	4.6

b) Spring barley stubble (2020): 9 - 25 years of repeated additions; treatment means (n=3)

Attribute[1]	Control	FYM (25yrs)	Slurry (25 yrs)	Green compost (15 yrs)	Green/food compost (9 yrs)	Food-based digestate (11 yrs)
SOM (%)**	2.7	3.2	2.9	3.4	3.3	2.9
pH **	6.3	6.7	6.5	6.7	6.4	6.4
Ext. P (mg/l)** [Index]	73 [5]	82 [5]	69 [4]	72 [5]	66 [4]	82 [5]
Ext. K (mg/l)** [Index]	82 [1]	212 [2+]	169 [2-]	144 [2-]	102 [1]	106 [1]
Ext. Mg (mg/l)** [Index]	33 [1]	69 [2]	62 [2]	50 [1]	55 [2]	47 [1]
VESS score	3	3	3	3	3	3
Earthworms (No/pit)	1	1	2	1	2	1
PMN (mg/kg)	24	37	29	37	31	28
CO_2-C burst (mg/kg)	84	111	108	109	112	99
MBC (mg/kg) [2]	114	138	138	134	123	129
Bulk density (g/cm^3) [2]	1.44	1.46	1.46	1.38	1.39	1.41
Penetration resistance (MPa) [2]	1.01	1.03	1.01	0.90	0.87	0.97

[1] See Table 3.4 for details of attributes measured; all properties measured to 15cm depth except penetration resistance where the maximum resistance to 30cm has been reported.

[2] These attributes are not part of the final scorecard and are therefore not benchmarked

**Attributes which showed a statistically significant difference between treatments (P<0.05)

In both sampling years, the results show the value of applying organic materials for increasing soil organic matter (SOM) contents on light textured soils, particularly bulky materials such as FYM and green compost ($P<0.05$). These materials provide valuable nutrients such as P and K (Table 3.3) and have a liming value, increasing soil nutrient indices and pH ($P<0.05$). However, soil extractable P levels at this site were inherently high (Index 4 on the control plots which received no manufactured fertiliser P for the duration of the experiment), resulting in an amber or red score (‘review/investigate’), given the potential risk of elevated P leaching losses from soils with high Olsen extractable P contents. Biological activity also increased where organic materials had been applied, with the lowest PMN, CO_2-C burst and MBC measured on the control plots. The highest microbial activity tended to be associated with the FYM treatment, although this was only statistically significant for PMN in 2017 ($P<0.05$). Earthworm numbers were not affected by organic material additions, and neither were any of the soil physical assessments ($P>0.05$).

By far the greatest differences were observed between the two sample timings and associated cropping/management, with SOM, structure and biological activity ‘poorer’ (amber/red scores) in 2020 following 3 years of arable cropping (including potatoes) compared with measurements in the grass ley in 2017 (Table 4.1a,b). Bulk density (at 5-10cm depth) also tended to be higher in 2020, although the maximum penetration resistance was lower (recorded at c. 25cm depth in both years). Soil moisture contents were similar at each sampling (17% in 2017, 18% in 2020) and the differences in resistance maybe a reflection of the presence of large grass ‘mat’ and mass of roots in 2017, compared to the cereal stubble in 2020 (after 3 years of plough-based cultivation).

4.2.2. Soil health scorecard at Gleadthorpe

The scorecard at Gleadthorpe (Table 4.2) showed a similar trend to the Harper Adams results with the application of organic materials, particularly bulky FYM and composts increasing SOM levels and providing nutrients ($P<0.05$). Whilst there was also some evidence of structural degradation (higher VESS score associated with surface capping and compaction) on the control treatment, the difference was not statistically significant, and there was no difference in bulk density or penetration resistance between treatments. Earthworm numbers were depleted across all treatments, which may reflect the light textured, low organic matter soils, but also the plough-based method of cultivation. PMN was lowest in the control treatment and where broiler litter had been applied ($P<0.05$), and CO_2-C burst and MBC were also numerically lower on the control than on the manure treatments although the difference was not statistically significant.

Table 4.2 Soil health scorecard (and additional measured attributes) following repeated organic material additions at Gleadthorpe (September 2019). Treatment means (n=3); organic materials repeatedly applied for 8-20 years.

Attribute[1]	Control	Broiler litter (20yrs)	Cattle FYM (8 yrs)	Cattle slurry (8 yrs)	Green compost (13 yrs)
SOM (%)**	1.9	2.1	2.7	2.2	2.8
pH **	6.8	6.6	7.9	7.4	7.5
Ext. P (mg/l)** [Index]	42 [3]	71 [5]	53 [4]	46 [4]	48 [4]
Ext. K (mg/l)** [Index]	96 [1]	192 [2+]	326 [3]	155 [2-]	177 [2-]
Ext. Mg (mg/l) [Index]	32 [1]	60 [2]	75 [2]	57 [2]	62 [2]
VESS score	3	2	2	2	2
Earthworms (No/pit)	0	1	0	1	0
PMN (mg/kg)**	12	26	31	36	35
CO_2-C burst (mg/kg)	68	85	80	82	77
MBC (mg/kg)[2]	96	129	164	181	153
Bulk density (g/cm^3) [2]	1.59	1.55	1.51	1.48	1.52
Penetration resistance (MPa) [2]	1.7	1.7	1.9	1.9	2.0

[1] See Table 3.4 for details of attributes measured; all properties measured to 15cm depth except penetration resistance where the maximum resistance to 30cm has been reported.

[2] These attributes are not part of the final scorecard and are therefore not benchmarked

**Attributes which showed a statistically significant difference between treatments (*P*<0.05)

4.2.3. Soil health scorecard at Terrington

The soil at Terrington had a higher clay content (medium-textured) and background SOM content on the control treatment compared to Gleadthorpe and Harper Adams (Table 3.1). However, the responses to organic material additions were similar (Table 4.3), with significant increases in topsoil SOM and nutrient status (*P*<0.05) and some evidence of poorer soil structural condition (higher VESS scores) and biological activity (lower PMN and CO_2-C burst) on the control treatment, although these were not statistically significant. Earthworm numbers indicated low/depleted levels of biological activity particularly on the control and pig slurry treatments, with higher (but not statistically significant) numbers recorded where pig FYM had been applied.

Table 4.3 Soil health scorecard (and additional measured attributes) following repeated organic material additions at Terrington (September 2020). Treatment means (n=3); organic materials repeatedly applied for 7-23 years

Attribute[1]	Control	Pig FYM (23 years)	Pig Slurry (23 yrs)	Green compost (13 yrs)	Green/food compost (7 yrs)	Food-based digestate (7 years)
SOM (%)**	3.5	3.9	3.5	4.1	3.6	3.4
pH	8.1	8.1	8.0	7.9	8.3	8.0
Ext. P (mg/l)** [Index]	11 [1]	42 [3]	24 [2]	20 [2]	17 [2]	17 [2]
Ext. K (mg/l)** [Index]	212 [2+]	440 [4]	427 [4]	361 [3]	287 [3]	275 [3]
Ext. Mg (mg/l) [Index]	224 [4]	193 [4]	210 [4]	211 [4]	209 [4]	156 [3]
VESS score	3	2	2	3	2	3
Earthworms (No/pit)	2	7	2	4	5	4
PMN (mg/kg)	32	42	47	46	37	51
CO_2-C burst (mg/kg)	44	71	45	67	51	50
MBC (mg/kg)[2]	299	339	288	266	242	279
Bulk density (g/cm^3) [2]	1.52	1.48	1.58	1.53	1.54	1.54
Penetration resistance (MPa) [2]	0.94	0.91	1.02	1.01	1.01	1.04

[1] See Table 3.4 for details of attributes measured; all properties measured to 15cm depth except penetration resistance where the maximum resistance to 30cm has been reported.

[2] These attributes are not part of the final scorecard and are therefore not benchmarked

**Attributes which showed a statistically significant difference between treatments (*P*<0.05)

4.2.4. Effect of repeated organic material additions on crop performance

Crop yields (Table 4.4) and the nutrient (N, P, K, Mg, S) content of the harvested materials (Appendices; Table 8.1 - Table 8.3) were measured every year from 2018 to 2020 at each site. There was no effect (*P*>0.05) of the repeated organic material additions on crop yields at Harper Adams (cereals and potatoes) or Terrington (cereals and sugar beet), although in most years, crop yields at these sites (except the potato crop at Harper Adams in 2019) were numerically higher where organic materials had been applied compared to the control treatment (results highlighted in grey in Table 4.4). For example, at Terrington, the highest yield each year was recorded on the long-term FYM application treatment. At Gleadthorpe, the repeated application of broiler litter resulted in higher spring barley yields in 2019 relative to the control treatment, with higher, but not statistically significant yields (*P*<0.1) also measured on this treatment in 2018 and 2020.

There were small but inconsistent treatment effects on some of the crop quality parameters measured at Harper Adams (e.g. grain Mg and S concentrations in 2018 and grain N in 2020), but no treatment effect on these properties measured in the harvested products at Terrington (Appendices: Table 8.1 – 8.3). At Gleadthorpe, the application of FYM, slurry and green compost resulted in higher grain N concentrations in spring barley at harvests 2018 and 2019 relative to the control treatment, with broiler litter also increasing grain N and P in 2019 (*P*<0.05; Appendices, Table 8.1 & 8.2). In 2020, there were significant differences in winter wheat grain N, P and K concentrations between treatments, with the lowest concentrations generally on the untreated control treatment (*P*<0.05; Appendices, Table 8.3).

Table 4.4 Crop yields at harvests 2018-2020 (treatment means; n=3). Crop yields in shaded boxes are numerically higher than the control.

Site:	Harper Adams	Gleadthorpe	Terrington
Crop 2018[1]:	WW t/ha @85%dm	SBa t/ha @85%dm	WW t/ha @85%dm
Control	6.4	2.7	11.1
FYM	7.2	2.1	11.3
Slurry	6.7	2.4	11.3
Green compost	6.7	2.9	10.9
Green/food compost	6.7		10.3
Food-based digestate	5.5		11.1
Broiler litter[2]	-	3.5	-
P[3]	*NS*	*NS*	*NS*
Crop 2019[1]:	Pot t/ha (FW)	SBa t/ha @85%dm	SB t/ha (adjusted yield)
Control	28	3.5^{a}	77.1
FYM	27	4.2^{ab}	83.6
Slurry	25	4.3^{ab}	80.5
Green compost	27	4.0^{ab}	78.7
Green/food compost	28		79.3
Food-based digestate	28		77.0
Broiler litter[2]	-	4.8^{b}	-
P[3]	*NS*	***0.05***	*NS*
Crop 2020[1]	SBa t/ha @85%dm	WW t/ha @85%dm	WW t/ha @85%dm
Control	3.9	3.2	12.0
FYM	4.6	2.6	12.8
Slurry	4.9	3.2	12.2
Green compost	4.0	3.2	12.8
Green/food compost	4.6		12.5
Food-based digestate	4.5		12.0
Broiler litter[2]	-	3.9	-
P[3]	*NS*	*NS*	*NS*

[1] Winter wheat grain; Sba: Spring barley-grain; Pot: Potato tuber yield – total marketable yield (size classes 45-65mm + 65-86mm combined); SB: Sugar beet – beet yield adjusted for sugar content

[2] Broiler litter only evaluated at Gleadthorpe

[3] Statistical analysis undertaken using ANOVA; there were three replicates of each treatment; *NS:* No significant difference (*P*>0.05). Numbers within a column labelled with different letters indicate significant differences between treatments at a site/year (*P*<0.05 using Duncans multiple range test)

4.2.5. Cross-site analysis

There were four common treatments across the three organic material experimental sites: control, FYM (cattle or pig), slurry (cattle or pig) and green compost. The results from these treatments were analysed using cross-site analysis of variance in order to see if there were any consistent treatment effects. Cereal grain yields recorded either the year prior to the soil health assessments (winter wheat at Terrington and spring barley at Harper Adams in 2020), or the year after the soil health assessments (winter wheat at Harper Adams in 2018 and at Gleadthorpe in 2020), were also included in this analysis. Although the year of sampling varied between sites, the sampling season did not (all sampled in either September or October).

Table 4.5 Summary of cross site analysis of the four 'core' treatments sampled at Harper Adams (in 2017 and 2020), Gleadthorpe (2019) and Terrington (2020)[1].

Attribute	Site	Treatment	Treatment x site
Soil chemical properties			
SOM	***	***	NS
pH	***	***	NS
Ext. P	***	***	NS
Ext. K	***	***	**
Ext. Mg	***	NS	NS
Soil biological properties			
PMN	**	***	***
CO_2-C burst	***	*	NS
MBC	***	NS	NS
Earthworms	***	NS	NS
Soil physical properties			
VESS	***	NS	NS
Bulk density	***	NS	NS
Penetration resistance	***	NS	NS
Crop performance			
Grain yield	***	NS	NS

[1]Anova tested for the effect of site, treatment, treatment x site interaction (i.e. is the effect of treatment the same at all sites?), where site location and timing of the sampling and treatment = control, FYM, slurry and green compost; *** P<0.001; ** P<0.01; *P<0.05; NS: No statistically significant effect (P>0.05).

Site had a highly significant effect (*P*<0.001) on all of the properties measured (Table 4.5), with site effects driven by the climate, soil type, previous management and cropping at the time of sampling (Table 3.1). For example, the medium-textured, silt clay loam soil at Terrington had a higher organic matter content than the light-textured sandy loam soils at both Gleadthorpe and Harper Adams, but the presence of a 2 year grass ley at Harper Adams improved SOM to a level similar to that on the arable soils at Terrington (Figure 4-1a). Similar trends were seen with a number of the soil biological properties measured, with higher earthworm numbers, PMN and microbial biomass (Figure 4-1b,c,d) measured on the medium textured soils at Terrington and in the grass ley at Harper Adams (2017), compared to the light textured, low organic matter arable soils at Gleadthorpe and Harper Adams (2020). An exception was microbial activity measured by CO_2-C burst which was highest in the grass ley at Harper Adams (Figure 4-1e), with the lowest activities recorded in the high pH soils at Terrington (pH 8.0, compared to pH 6.5-7.0 at the other sites). The 'best' soil structure (lowest VESS score) was also recorded in the grass ley at Harper Adams (Figure 4-1f).

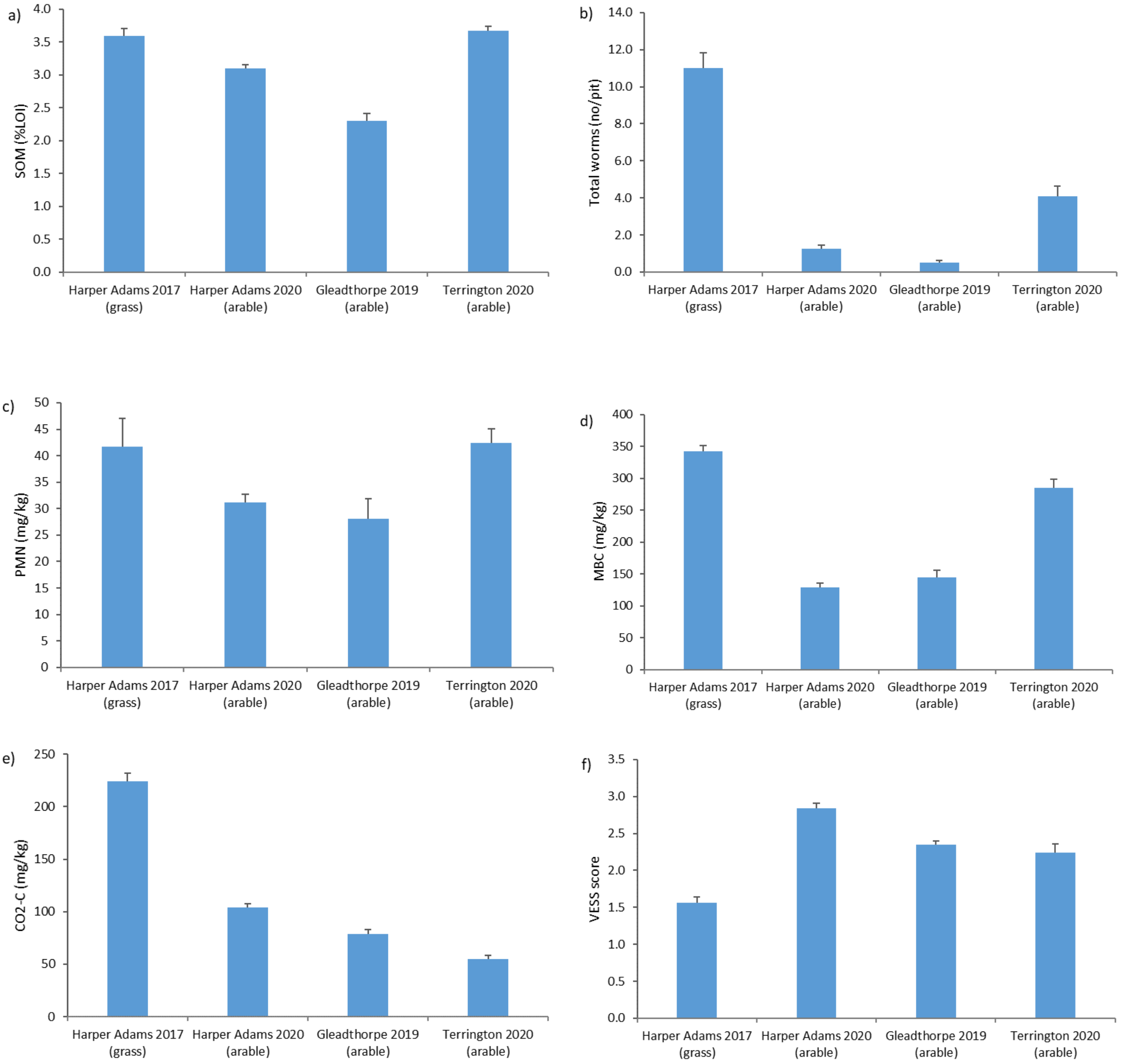


Figure 4-1 Topsoil properties at each of the sites, averaged across all the organic material treatments; a) SOM, b) worm count,c) potentially mineralizable N, d) microbial biomass carbon, e) CO_2-C burst, f) Visual evaluation of soil structure limiting layer score. Differences between the sites were statistically significant, $P<0.001$.

The organic material additions had a consistent effect across all three sites on the majority of soil chemical and some of the biological properties measured, with very little site by treatment interaction (Table 4.5). The only exceptions to this were for topsoil extractable K where the highest concentrations were consistently measured following the FYM treatment, but differences between the other organic material treatments were more variable. Likewise, although all organic materials increased PMN content relative to the control, the difference between organic materials differed across the sites. The results demonstrated that soil organic matter, CO_2-C burst, pH and extractable P showed a consistent response to the organic material additions with SOM levels increased by repeated organic material addition in the order green compost>FYM>slurry, but CO_2-C burst and pH in the order FYM>green compost>slurry. Extractable P levels were most markedly changed following the application of FYM across all the sites. There was no consistent effect of the organic material additions on the range of soil physical properties measured.

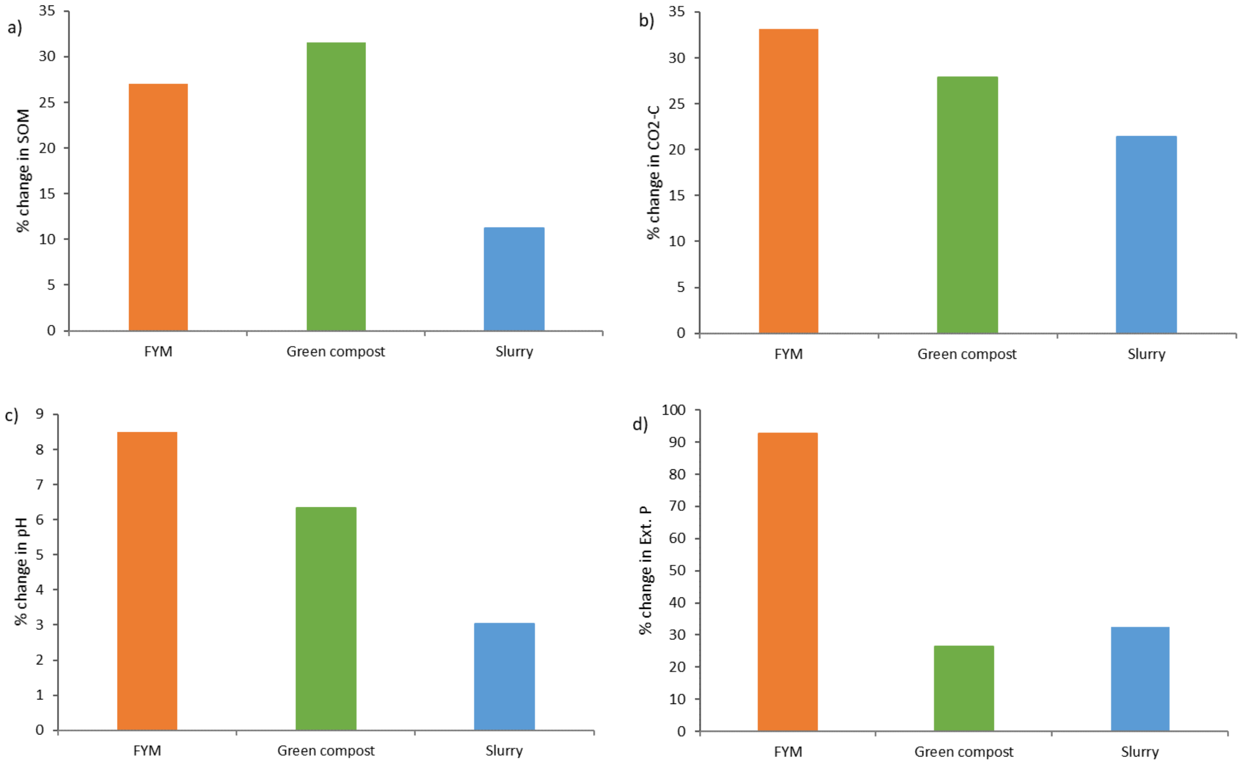


Figure 4-2 Change in soils properties following the repeated addition of FYM, green compost and slurry, a) SOM, b) CO_2-C burst, c) pH, d) extractable P. Results are expressed as a percentage difference from the control treatment averaged over four site/sampling timings. Differences between treatments were statistically significant ($P<0.05$) in a cross site analysis with no site x treatment interaction ($P>0.05$).

4.2.6. Relationships between soil properties and crop performance at the long-term organic material sites

The relationship between the soil chemical and biological properties assessed by the health scorecard and grain yield was explored using parallel line regression analysis (where the response was grain yield and predictors were the scorecard indicators: SOM, pH, Ext. P & K, PMN, CO_2-C burst and earthworms), with the analysis restricted to the common treatments at each of the experimental sites. Soil physical properties (i.e., VESS, bulk density and penetration resistance) were excluded from this analysis as no statistically significant treatment effect was observed in the cross-site analysis of variance. First a single line was fitted to the combined site data (n=36; 4 treatments x 3 reps x 3 sites), then, as the cross-site analysis indicated a significant site effect, separate parallel lines were fitted to each site (n=12), keeping the slope constant but allowing the intercept to vary i.e., this assumed a consistent response across all sites from different baselines. Finally, the model evaluated whether there was a different relationship at each of the sites by allowing both the intercept and slope to vary (n=12). In all cases, fitting parallel lines improved the model fit (Table 4.6) due to the highly significant site differences reported by the cross-site analysis. However, for most properties, fitting individual lines (i.e. allowing both the slope and intercept to vary) did not improve the fit. The best fit was when a consistent response between soil properties and yield across all sites was assumed.

Table 4.6 Parallel line analysis exploring the relationship between the soil health scorecard properties and cereal grain yields at the long-term organic material experimental sites.

Predictor (soil property)	Percentage of variance in grain yield accounted (direction & slope of relationship)[1]		
	Single line[2]	Parallel lines[2]	Individual lines[2]
SOM	44.0 (+ 3.62)	93.1 (+ 0.686)	93.1 (+/-)
pH	23.2 (+ 2.79)	92.7 (- 0.552)	93.4 (-)
Ext P	32.4 (- 0.104)	93.2 (+ 0.031)	92.9 (+/-)
Ext K	43.1 (+ 0.022)	92.7 (+ 0.002)	92.4 (+/-)
PMN	9.8 (+ 0.075)	93.2 (+ 0.016)	92.7 (+)
CO_2-C burst	0	93.5 (+ 0.018)	93.4 (+)
Worms	4.2 (+ 0.197)	92.6 (+ 0.068)	92.3 (+/-)

[1] Direction of relationship refers to whether there was a positive (+) relationship between the soil property and yield, or negative (-). Numbers after the symbol refer to the slope (only given for single and parallel lines). +/- indicates a difference in the response direction between sites.

[2] Single line fitted to all site data; separate parallel lines fitted to each site keeping the slope constant; separate individual lines fitted to each site with both slope and intercept allowed to vary.

The ‘best’ single line relationship was observed between SOM and grain yield, with topsoil SOM levels explaining 44% of the variation in cereal grain yields across all sites (measured either the harvest before or after the soils were assessed); this was improved to 93% of the variance accounted for by taking into account site differences (i.e. allowing the intercept to vary), with yields increasing by 0.69 t/ha with every 1% higher SOM content on a site-by-site basis (Table 4.6, Figure 4-3). Grain yields also increased with increasing soil extractable K levels at all sites (by 0.02 t/ha with every 10 mg/l increase in ext. K), but for extractable P, a negative relationship was observed using the combined site data. This was most likely due to differences in soil type and underlying geology, with inherently high P levels in the sandy loam soils at Harper Adams, but relatively low grain yields, as a result of other soil factors including low available water capacity. This was in contrast to Terrington, where extractable soil P levels were low (reflecting the calcareous nature of the soil) and crop yields were high due to the higher available water capacity of the silty clay loam soil. On a site-by-site basis, the relationship between soil P and crop yields was positive (i.e. higher yields with higher extractable P levels). The relationship between pH and crop yields was also had a positive across all sites, largely driven by the high yields recorded on the calcareous soils at Terrington. On a site-by-site basis there was insufficient variation in pH to test the relationship. There was no relationship between grain yields and PMN, CO_2-C burst and earthworms across the combined site data (<10% of the variation in yield explained by these properties from the single line fit). The relationship improved by taking site into account, with higher grain yields generally associated with higher PMN, CO_2-C burst and earthworm numbers, although the range in the data for these properties was relatively low.

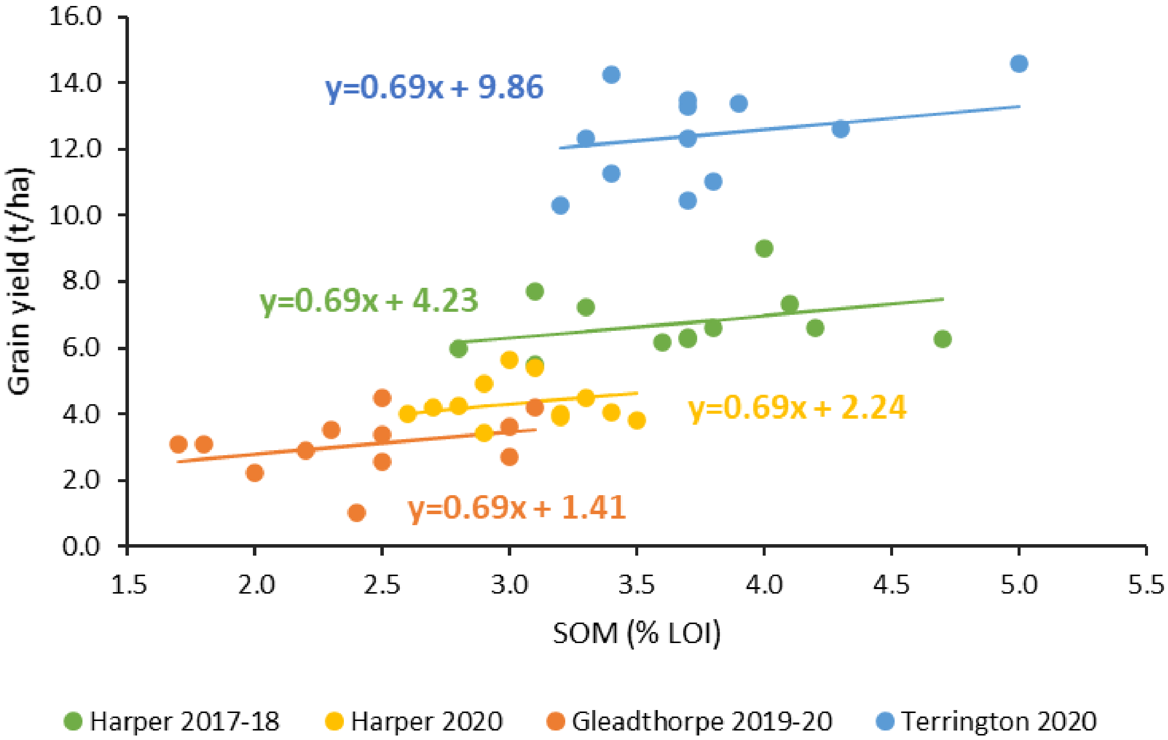


Figure 4-3 Relationship between topsoil organic matter content and cereal grain yield (winter wheat at Gleadthorpe, Terrington and at Harper Adams in 2017-18, spring barley at Harper Adams in 2020); 93% of the variance in yields across the sites could be accounted for by 'site' and topsoil organic matter content.

4.3. Effect of tillage and drainage status on soil health and crop performance

4.3.1. Effect of ploughing a long-term no till field on soil health (Loddington)

Soil health assessments were undertaken at Loddington in September 2018, one year after ploughing three strips of a field that had been no till for 7 years, with assessments repeated in September 2020 after three years of annual ploughing and 10 years of no tillage (Table 4.7). On both occasions the field was in cereal stubble.

There was very little difference between the tillage treatments at both samplings ($P>0.05$ for most soil properties), with the majority of soil properties given a ‘green’ light according to the soil health scorecard benchmarks. One year after cultivation, the ploughed treatment had a lower number of earthworms (predominantly topsoil or endogeic worms), although variability across the field meant this was not a statistically significant effect. In 2020, the sampling followed a period of dry weather and numbers of earthworms were low across both treatments. In 2020, there was also a tendency for SOM and the soil microbial indicators, PMN, CO_2-C burst and MBC to be higher in the direct drill treatment, although this was largely driven by one replicate strip and was not statistically significant.

Table 4.7 Soil health scorecard (and additional measured attributes) of ploughed and continuous no till (direct drill) treatments at Loddington.

Attribute[1]	Plough		Direct drill	
	2018	2020	2018	2020
SOM (%)	7.1	7.1	7.2	7.9
pH	6.8	7.4	7.2	7.4
Ext. P (mg/l) [Index]	22 [3]	21 [3]	26 [3]	28 [3]
Ext. K (mg/l) [Index]	162 [2-]	137 [2-]	140 [2-]	173 [2-]
Ext. Mg (mg/l) [Index]	126 [3]	119 [3]	104 [3]	98 [2]
VESS score	2	3**	2	2**
Earthworms (No/pit)	6	5	10	5
PMN (mg/kg)	71	54	74	95
CO_2-C burst (mg/kg)	143	101	139	116
MBC (mg/kg)[2]	401	330	394	419
Bulk density (g/cm^3)[2]	1.3	1.1	1.4	1.1
Penetration resistance (MPa)[2]	3.2	2.4	3.2	2.4

[1] See Table 3.4 for details of attributes measured; all properties measured to 15cm depth except penetration resistance where the maximum resistance to 30cm has been reported.
[2] These attributes are not part of the final scorecard and are therefore not benchmarked
**Statistically significant treatment effect using a t test ($P<0.05$)

There was a difference in the limiting layer VESS score in 2020 ($P<0.05$), with a higher score recorded on the plough treatment suggesting a more compact layer at *c.*15cm depth compared to the direct drill treatment (which also had a layer at *c*.15cm but with a lower score). However, there were no differences in soil bulk density (measured at 5-10cm depth) or penetration resistance (maximum resistances were recorded at 30cm depth).

4.3.2. Effect of ploughing a long term no till field on crop performance (Loddington)

There was no difference ($P>0.05$) in cereal grain yields (Table 4.8) or nutritional quality (Appendix Table 8.4) between the two tillage treatments over the course of the three year experimental programme.

Table 4.8 Grain yields (t/ha @ 85% dm) at Loddington 2018-2020 (treatment means, n=3, with standard errors in brackets).

Harvest year	Plough	Direct drill	P value[1]
2018 (winter wheat)	6.8 (0.24)	6.7 (0.25)	*NS*
2019 (winter oats)	4.5 (0.39)	4.9 (0.05)	*NS*
2020 (spring wheat)	4.9 (0.31)	4.6 (0.71)	*NS*

[1] P value from t-test (2 treatments replicated 3 times); NS = not significant (*P*>0.05)

4.3.3. Effect of drainage improvement on soil health (Boxworth)

There was no difference (*P*>0.05) in soil properties between soils where drainage had been improved (mole drained in 2017) compared to where it hadn't (mole drained in 2007); Table 4.9. The soils were calcareous (pH>7.5) heavy clays (>40% cl) with a high SOM content (low rainfall region), low extractable P content (Index 1) and low earthworm count (plough-based crop establishment). Soil microbial activity, as measured by the CO_2-C burst methodology was also low. There was no difference in soil structural condition, with 'good' VESS scores for both treatments, although penetration resistance was numerically lower on the improved drainage treatment.

Table 4.9 Soil health scorecard (and additional measured attributes) at Boxworth, September 2020 (cereal stubble)

Attribute[1]	**Drainage status**	
	Unimproved	**Improved[3]**
SOM (%)	**5.3**	**5.4**
pH	**7.9**	**7.7**
Ext. P (mg/l) [Index]	**13 [1]**	**11 [1]**
Ext. K (mg/l) [Index]	**213 [2+]**	**232 [2+]**
Ext. Mg (mg/l) [Index]	**74 [2]**	**74 [2]**
VESS score	**2**	**2**
Earthworms (No/pit)	**5**	**5**
PMN (mg/kg)	**45**	**39**
CO_2-C burst (mg/kg)	**59**	**56**
MBC (mg/kg)[2]	339	323
Bulk density (g/cm^3)[2]	1.38	1.43
Penetration resistance (MPa)[2]	1.15	0.83

[1] See Table 3.4 for details of attributes measured
[2] These attributes are not part of the final scorecard and are therefore not benchmarked.
[3] Mole-drained in 2017 (unimproved treatment last mole-drained in 2007)

4.3.4. Effect of drainage improvement on crop performance (Boxworth)

There was no difference (*P*>0.05) in cereal grain yields (Table 4.10) or nutritional quality (Appendix Table 8.5) between the two drainage treatments over the course of the three year experimental programme.

Table 4.10 Grain yields (t/ha @ 85% dm) at Boxworth 2018-2020 (treatment means, n=3 with standard errors in brackets).

Harvest year	Unimproved drainage	Improved drainage	P value[1]
2018 (winter barley)	7.9 (0.76)	8.9 (0.16)	NS
2019 (spring barley)	7.3 (0.28)	7.2 (0.08)	NS
2020 (spring barley)	6.8 (0.71)	6.6 (1.43)	NS

[1] P value from t-test (2 treatments replicated 3 times); NS = not significant ($P>0.05$)

4.4. Effect of crop rotation, pH and nutrient supply on soil health and crop performance

4.4.1. Effect of pH on soil health (Craibstone pH trial)

Soil health assessments were undertaken in October 2018 from four crops (2nd year ley, following winter wheat, potatoes and spring oats; the potato crop was still in the ground at the time of sampling, but the cereal crops had been harvested) at four pH levels (4.5, 6.0, 6.5 and 7.5). Table 4.11 demonstrates the effect of pH averaged across all four crop types, with the measured soil pH close to or at the treatment target pH. The results show a clear effect of low soil pH (pH 4.5) on a number of soil properties – particularly nutrient availability and biological activity. As the site is in Scotland, soil nutrient status was measured using SAC methodologies and interpretation framework (Technical note 633, which classifies soil nutrient status from very low to very high). Extractable P concentrations were elevated at low pH ($P<0.05$), whereas extractable K and Mg were reduced, with the highest concentrations of these two nutrients measured at pH 7.5 ($P<0.05$), and Mg concentrations in particular very low at pH 4.5.

There was no effect of soil pH on SOM levels ($P>0.05$), but soil biological properties, i.e. earthworm numbers, PMN, CO_2-C burst and MBC were all significantly lower at pH 4.5 ($P<0.05$), with no difference in earthworm numbers at pH 6.0 – 7.5, whereas soil microbiological properties tended to be highest at pH 6.5 with intermediate levels measured at pH 6 and 7.5 (although this pattern of response varied with crop type, section 4.4.3).

Table 4.11 Soil health scorecard (and additional attributes) as affected by pH at Craibstone (average across 4 different crop types)

Attribute[1]	pH 4.5	pH 6	pH 6.5	pH 7.5
pH **	4.9	6.1	6.6	7.5
SOM (%)	10.3	10.1	10.3	10.3
Ext. P (mg/l)** [Status]	22 [H]	11 [M+]	10 [M+]	15 [H]
Ext. K (mg/l)** [Status]	127 [M-]	130 [M-]	146 [M-]	154 [M-]
Ext. Mg (mg/l)** [Status]	18 [VL]	74 [M]	106 [M]	121 [M]
VESS score**	2	1	2	1
Earthworms (No/pit)**	1	5	5	6
PMN (mg/kg)**	62	67	77	75
CO_2-C burst (mg/kg)**	99	124	140	101
MBC (mg/kg)[2**]	98	157	231	163
Bulk density (g/cm^3)[2]	0.96	1.06	1.04	1.00
Penetration resistance (MPa)[2**]	4.0	4.0	3.6	3.1

[1] See Table 3.4 for details of attributes measured; all properties measured to 15cm depth except penetration resistance where the maximum resistance to 30cm has been reported. Extractable nutrients interpreted using SAC Technical Note 633: VL = very low, M= moderate, H = High.

[2] These attributes are not part of the final scorecard and are therefore not benchmarked

**Attributes which showed a statistically significant difference between pH treatments ($P<0.05$)

Soil structural condition was ‘good’ (limiting layer scores of 1 or 2) across all the pH levels, and although the ANOVA indicated a statistically significant effect of pH, the response was inconsistent with crop type ($P<0.001$ for the interaction between pH and crop) and the variation in scores across the treatments was low. There was no effect of pH on soil bulk density, but penetration resistance was lower ($P<0.05$) at pH 7.5, with very high resistances measured on all treatments (>2MPa is considered to impede root elongation, Valentine *et al*. 2012).

4.4.2. Effect of soil pH on crop yields and quality

Table 4.12 gives the yields of the four crops in 2018 determined either prior to (cereals and grass) or after (potatoes, which were still in the ground at the time of the soil sampling) the soil assessments. The highest winter wheat yields were measured at pH 6.0 and 6.5, with no measurable crop yield at pH 4.5 and very low yields at pH 7.5. Hay yields also peaked at pH 6 – 6.5, whereas the maximum potato and oat yields were recorded at pH 5.5 and pH 5.0, respectively. The long-term 48-year average cereal yields confirm these trends, with wheat and barley particularly sensitive to both low and high pH levels and producing maximum yields at pH 5.5-6.0. The oat crop less sensitive to low pH, with maximum yields at pH 5.0-5.5 (Figure 4-4).

Table 4.12 Effect of soil pH on crop yields at harvest 2018 (maximum yields highlighted)

Crop	pH 4.5	pH 5.0	pH 5.5	pH 6.0	pH 6.5	pH 7.0	pH 7.5
Wheat (t/ha @ 85%dm)	0	3.12	4.77	8.60	7.84	6.76	2.36
Oats (t/ha @ 85% dm)	3.90	3.58	3.54	3.18	2.66	2.06	1.33
Hay (t/ha)	7.25	8.74	8.85	9.52	9.77	8.36	6.68
Potatoes (t/ha)	44.3	53.0	55.1	54.1	51.5	48.0	46.3

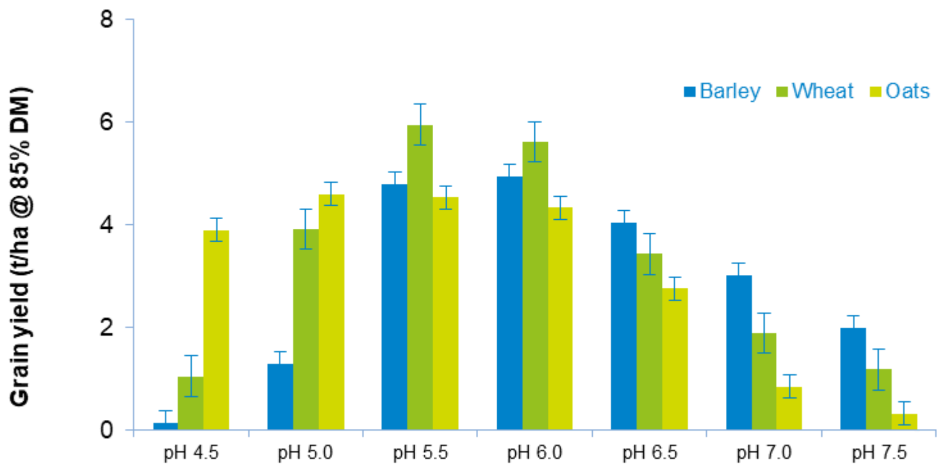


Figure 4-4 Average cereal grain yields at Craibstone long-term pH trial (48 year average)

Long-term (2002-2007) average cereal grain N concentrations are reported in Appendix Figure 8.1 and show a clear effect of soil pH, with highest grain N concentrations in the barley and wheat crops recorded at pH 7.5, with very little variation in oat grain N concentrations.

4.4.3. Effect of crop rotation (Craibstone pH trial)

Table 4.13 demonstrates the effect of crop type on soil properties, averaged across the four different pH levels. The Countesswell series soil has a median SOM content of 10% (Soil Information For Scottish Soils – SIFSS; https://sifss.hutton.ac.uk/SSKIB_stats.php). SOM contents were at or above 10% for all the crops except oats (undersown with grass), which had a lower SOM content than the other crop types ($P<0.05$). Crop type also had an effect on soil nutrient status, physical condition and soil biology ($P<0.05$). Soil nutrient status was highest in the potato crop, reflecting the pre-planting FYM application and high manufactured fertiliser P & K inputs (30 t/ha FYM, 150 kg P_2O_5/ha and 120 kg K_2O/ha applied to the potato seedbed, compared to 50-65 kg P_2O_5/ha and 70-85 kg K_2O/ha applied to the cereal crops in the rotation, with no fertiliser applied to the grass/clover ley). Soil structural condition was good under all crop types, with the lowest VESS scores ('friable' soil structure) recorded in the potato and oat crops. Penetration resistance and bulk density was also lowest in the potato crop, reflecting the cultivations required for crop establishment.

On average over the pH treatments, earthworm numbers were lowest in the oat and potato crops ($P<0.05$), but the response varied with pH, with the highest earthworm numbers recorded in the grass ley at pH 6 followed by the wheat crop at pH 7.5, and the lowest numbers recorded in the potato and oat crops at pH 4.5 (Figure 4-5). Similarly, the soil microbial attributes measured (PMN, CO$_2$-C burst and MBC) varied by both crop type and pH (Figure 4-5), although these attributes tended to be at their lowest level in the oat crop.

Table 4.13 Soil health scorecard (and additional attributes) as affected by crop type at Craibstone (average across 4 different pH levels)

Attribute[1]	Oats	Grass	Wheat	Potatoes
SOM (%)**	9.8	10.6	10.5	10.0
Ext. P (mg/l)** [Status]	14 [H]	13 [M+]	15 [H]	15 [H]
Ext. K (mg/l)** [Status]	149 [M+]	123 [M-]	115 [M-]	170 [M+]
Ext. Mg (mg/l)** [Status]	77 [M]	78 [M]	77 [M]	88 [M]
VESS score**	1	2	2	1
Earthworms (No/pit)**	3	8	5	2
PMN (mg/kg)**	61	72	75	73
CO$_2$-C burst (mg/kg)**	121	127	100	116
MBC (mg/kg)[2]	146	164	148	191
Bulk density (g/cm^3)[2]**	1.1	1.1	1.0	0.8
Penetration resistance (MPa)[2]**	4.6	4.2	3.7	2.3

[1] See Table 3.4 for details of attributes measured; all properties measured to 15cm depth except penetration resistance where the maximum resistance to 30cm has been reported. Extractable nutrients interpreted using SAC Technical Note 633: M= moderate, H = High.

[2] These attributes are not part of the final scorecard and are therefore not benchmarked

**Attributes which showed a statistically significant difference between treatments ($P<0.05$)

Soil physical condition was ‘good’ across the site except for on the fertilised grassland which scored ‘moderate’ for soil structure suggesting slightly denser soils (although this difference was not statistically significant). This was supported by the bulk density and penetration resistance measurements which were highest in the undisturbed grassland soils and lowest in the potato crop ($P<0.05$). Fertiliser addition had no effect on soil physical condition, except for penetration resistance which was lower where fertiliser had been applied in all but the oat crop ($P<0.05$).

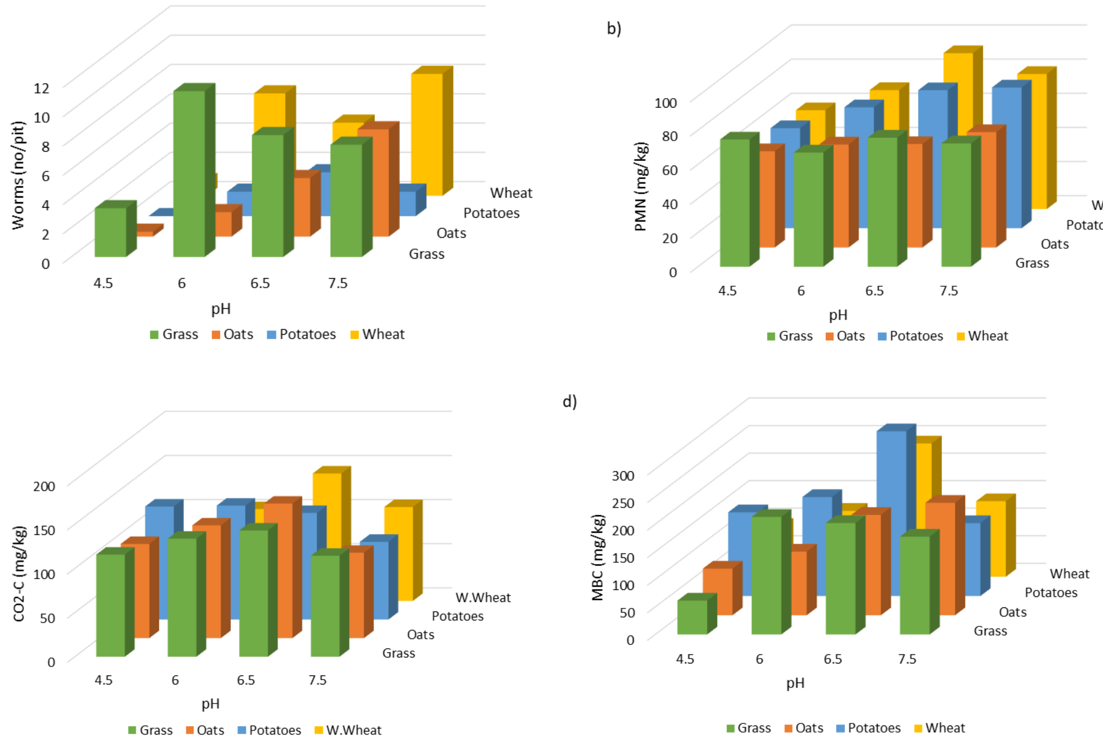


Figure 4-5 Effect of crop type and pH on soil biology: a) earthworm numbers, b) Potentially Mineralisable Nitrogen – PMN, c) CO_2-C burst, d) Microbial biomass carbon (MBC).

4.4.4. Effect of crop rotation and fertiliser inputs (Craibstone crop rotation trial)

The scorecard for the crop rotation trial at Craibstone is shown in Table 4.14. Not surprisingly, the absence of fertiliser (NPK) had a significant effect on soil nutrient status, with both extractable P and K levels higher where fertiliser had been applied ($P<0.05$), but Mg levels un-affected as Mg fertiliser was not applied to either treatment. Crop type had no effect on extractable P, whereas extractable K was highest in the potato crop and lowest in the grass ley, most likely reflecting the level of K inputs to the potato crop (in both FYM and manufactured fertiliser). Long-term fertilisation and crop type did not have an effect on soil pH, which was relatively low across the site (pH 5.9-6.3), with lime typically applied to the spring barley crop (last applied in March 2017). Likewise, there was no consistent effect of crop type and fertiliser on SOM levels ($P>0.05$).

Table 4.14 Soil health scorecard (and additional attributes) as affected by crop type and fertiliser (either 'Nil' or complete 'NPK') a Craibstone Rotations trial

Attribute[1]	Grass ley		Oats		Potatoes		Barley	
	Nil	NPK	Nil	NPK	Nil	NPK	Nil	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)* [Status]	3 [L]	8 [M-]	3 [L]	8 [M-]	3 [L]	8 [M-]	3 [L]	7 [M-]
Ext. K (mg/l)*** [Status]	50 [L]	60 [L]	60 [L]	98 [M-]	116 [M-]	162 [M+]	68 [L]	117 [M-]
Ext. Mg (mg/l)** [Status]	157 [M]	173 [M]	108 [M]	152 [M]	168 [M]	148 [M]	99 [M]	93 [M]
VESS score**	2	3	2	2	1	2	2	2
Earthworms (No/pit)**	18	13	8	6	5	4	5	10
PMN (mg/kg)	42	38	44	43	44	45	42	43
CO_2-C burst (mg/kg)	123	117	116	101	125	135	123	126
MBC (mg/kg)[2]**	479	452	452	356	392	364	409	429
Bulk density (g/cm^3)[2]**	1.1	1.2	0.9	0.9	0.9	0.9	1.0	1.1
Penetration resistance (MPa)[2]***	2.0	1.8	1.1	1.2	0.4	0.3	1.3	1.1

[1] See Table 3.4 for details of attributes measured; all properties measured to 15cm depth except penetration resistance where the maximum resistance to 30cm has been reported. Extractable nutrients interpreted using SAC Technical Note 633: M= moderate, H = High.

[2] These attributes are not part of the final scorecard and are therefore not benchmarked

*Attributes which showed a statistically significant difference due to fertiliser treatment, but not crop type ($P<0.05$)

**Attributes which showed a statistically significant difference between crop types, but not fertiliser treatment ($P<0.05$)

***Attributes which showed a statistically significant difference between crop type and fertiliser treatment ($P<0.05$).

There was no effect of fertiliser treatment on soil biological attributes ($P>0.05$), which probably reflected the absence of an effect on SOM contents. However, both earthworm numbers and microbial biomass were highest in the grass ley and lowest in the potato crop ($P<0.05$).

4.4.5. Effect of fertiliser input on crop performance (Craibstone old rotation)

Only a single measurement of crop yield was carried out in each year from the treatments (with no replication of measurements). In order to evaluate the effect of fertiliser addition on crop yield, Figure 4-6 shows the average yield achieved over 6 years with its associated standard error. As expected, fertilised treatments consistently produced higher yields than unfertilised treatments, with the increase most pronounced for the hay (grass ley).

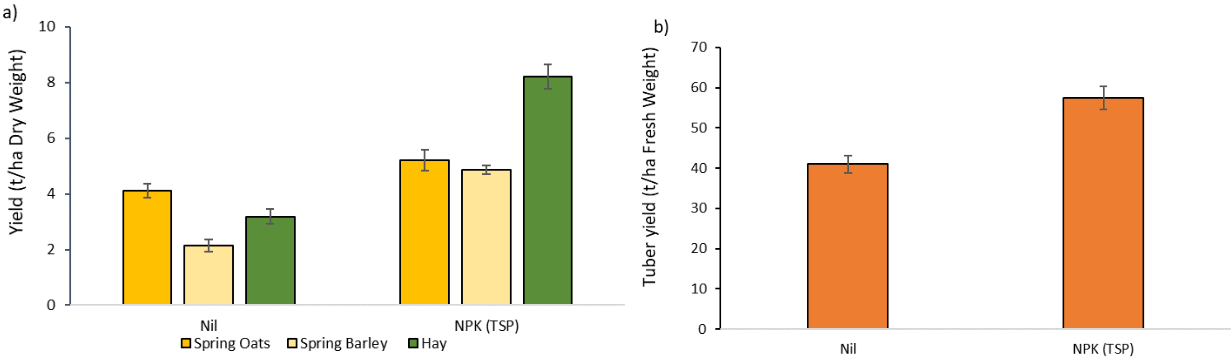


Figure 4-6 Crop yields (6-year averages) for unfertilised and fertilised soils under a) oats, barley and grass ley and b) potatoes.

4.5. Microbial indicators of soil health

The size and activity of the soil microbial biomass is considered to be a key indicator of soil biological health. The standard chloroform method (MBC) is not a commercially available technique, so Project 11 evaluated two alternative methods of estimating the size and activity of the soil microbial community: PMN and CO_2-C burst. Project 5 also estimated total bacteria (16S rRNA) and fungi (18s rRNA) at each of the sites, using qPCR analysis of the extracted microbial DNA (see Project 5 report for the methodology). Over all 7 sites and treatments (116 soil samples in total), the microbial pool was estimated using four different methodologies: MBC (chloroform), PMN, CO_2-C burst and DNA (total bacteria and fungi). Relationships between the four methodologies were explored using correlation and regression analysis techniques.

Across the combined site data (n=116) there was no relationship between bacteria and CO_2-C burst or between PMN and MBC, and weak relationships with most of the other microbial indicators (Table 4.15). There was some indication of a relationship between PMN and Fungal DNA, however there was a considerable number of soils with low fungal biomass and wide ranging PMN levels, with the Craibstone pH and Loddington experiments dominating the relationship (Figure 4-7). As there was a significant effect of ‘site’ on these properties (as seen in the cross-site analysis of the organic material sites and in the more detailed analysis of the extracted DNA – see Project 6 report), it is more appropriate to evaluate the relationships on a site-by-site basis. However, at an individual site level, there was also poor correlation between the different microbial indicators (Appendix, Table 8.6). The ‘best’ relationships (highest R^2 values) were observed at Loddington, but these were driven by one replicate plot of the direct drill treatment which had a high SOM content, MBC, CO_2-C burst, PMN, bacterial biomass and to a lesser extent fungal biomass.

Table 4.15 Correlation Matrix for the relationship between five measures of the soil microbial community (n=116).

Indicator	Bacterial DNA (16S rRNA)	Fungal DNA (18S rRNA)	MBC	PMN
Bacterial DNA (16S rRNA)				
Fungal DNA (18S rRNA)	-0.42			
MBC	0.30	-0.28		
PMN	-0.44	0.68	-0.05	
CO_2-C burst	0.00	0.34	0.16	0.45

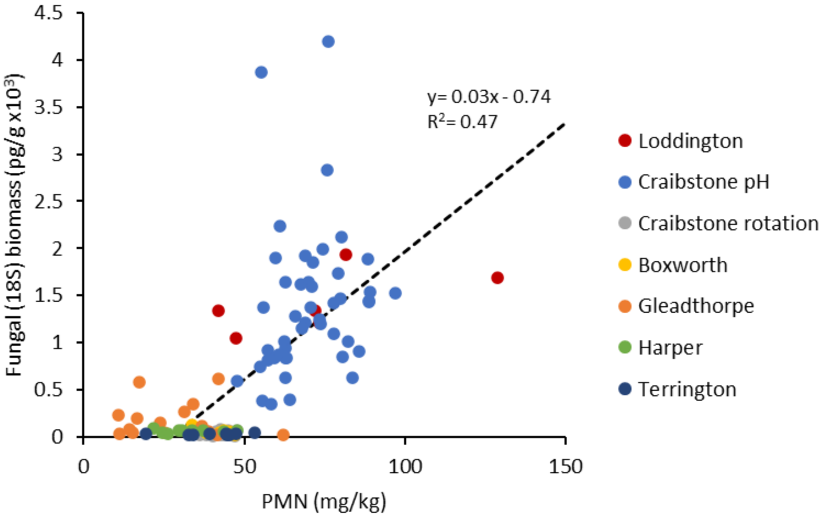


Figure 4-7 Relationship between PMN and Fungal biomass (18S rRNA) across the combined site data

5. Discussion

Soil health has been the subject of multiple publications in recent years, for example a web of science search using the terms ‘soil’ AND ‘health’ revealed almost 400 papers published in 2021 on the subject. This included widespread debate about what is meant by the term ‘soil health’ (e.g. Baveye, 2021; Powlson, 2021, Janzen *et al.* 2021), with a recognition that it is dependent on the function of soils within the boundaries of land use, climate and soil type (i.e. it depends what the soil is being used for, where it is and its inherent properties). Most definitions highlight the fact that soils are living systems (e.g. FAO, 2008), demonstrating the importance of soil biology, alongside a soil’s physical and chemical properties which is reflected in the importance of the scorecard approach to evaluate soil physical, chemical and biological indicators of soil health.

5.1. Food source as a driver of soil biological functioning

Soil biology ultimately relies on organic matter for energy and nutrients. Soil organic matter content can be manipulated using external organic matter inputs such as organic materials, but inputs are also dependent on crop choice and rotation (i.e., root and residue returns).

5.1.1. Effect of organic material inputs

The results from the long-term organic material sites confirmed the value of applying organic materials to agricultural soils as a source of both nutrients and organic matter, with some also having value as a liming material (Johnston *et al.,* 2009, Bhogal *et al.,* 2018). It is important that applications are appropriately managed to avoid excess nutrient accumulation, particularly in the case of phosphorus, which presents a potential risk to the environment (water quality) at high soil P levels (Index 4+; Withers *et al.* 2017). The measurements in this project confirmed that improvements in SOM and soil biological properties were largely associated with the application of bulky, high dry matter materials such as FYM and compost, compared to the slurry and digestate applications (Bhogal *et al.*, 2009, 2018).

Cross site analysis demonstrated a clear and consistent effect of organic material additions on SOM content, pH, nutrient concentrations, and CO_2-C burst, but not soil physical properties. SOM levels increased by repeated organic material additions in the order green compost>FYM>slurry, but CO_2-C burst (i.e. microbial activity) increased in the order FYM>green compost>slurry, suggesting differences in response associated with the ‘quality’ of the material applied. The extent of decomposition of organic matter that is added to soil is one of the important factors that define the “quality” of the amendment. This is discussed further by Bhogal *et al.* (2018), who, found that whilst green compost was a good source of stable organic matter able to build-up SOM over a relatively short time-frame, it did not produce the same level of improvement in associated soil biological and physical functioning as a similar increase in SOM produced by FYM applications. They found that, the more readily decomposable carbon source provided by FYM supported a larger microbial population than that produced by the green compost additions.

The cross-site analysis also clearly showed the importance of ‘site factors’, such as soil texture and climatic region, but also previous management history (e.g. presence of grass in the rotation such as at Harper Adams) in controlling soil organic matter levels, with differences between sites greater than the differences associated with organic material addition. For example, the presence of grass on the sandy loam soil at Harper Adams resulted in a similar SOM content to the silty clay loam soil under arable cultivation at Terrington, both of which were higher than in the arable phase of the rotation at Harper Adams and the light-textured soils at Gleadthorpe.

Statistically significant effects of the organic material treatments on grain yield were only observed in spring crops on the light textured, low organic matter soils at Gleadthorpe. This supports the findings of Whitmore *et al*. (2017), who found spring crops benefited more from organic amendments than winter crops, although this was less clear in years when overall yields were high. This suggests that organic material additions are most beneficial to crop performance in ‘stressed’ situations caused by extremes of weather (e.g. too dry) and on sensitive soil types (e.g. sandy soils with a reduced capacity for nutrient and water retention). However, although there was no treatment effect on yield at most sites and years, there was a clear positive relationship between SOM content and grain yield across the sites. This may reflect elevated nutrient supply from the repeat applications of organic manure. There were also positive relationships between Ext P and K concentrations and yield, even though fertilisers were applied to ensure optimal nutrient supply cross all treatments. The relationship between yield and soil biology was also positive on a site-by-site basis. Whitmore *et al* (2017) suggested that improvements in soil biology following organic material additions would be expected to lead to improved soil structure, which in turn would lead to higher yields due to better rooting. However, the cross-site analysis showed that there was no consistent effect of long-term organic material applications on VESS scores, bulk density and penetration resistance. Changes in soil physical properties following organic material additions can be slow to develop and difficult to detect, particularly if a soil has relatively good structure initially, with differences in cultivation practices typically having a greater effect.

5.1.2. Effect of crop rotation

Crop rotation influences soil health by the combined effects of crop type and soil management practice at the different points in the rotation. The sequence of crops in rotation and how they are managed not only influences nutrient inputs and offtake, but also controls the amount of residue that is returned, the level of soil disturbance, and the development of biopores by crop roots. These factors all control soil nutrient status, organic matter content, structure and biological activity (Ball *et al.,* 2005).

The benefit of having grass in the rotation can be clearly seen from the comparison of scorecards carried out at Harper Adams on the grass ley in 2017 and after three years of arable cropping (including potatoes) in 2020. Soils in the arable phase of the rotation had lower SOM levels, earthworm numbers and microbial biomass and activity, but higher VESS scores which indicates poorer soil structure than on the grass ley.

The two crop rotation experiments at Craibstone had all phases of the rotation present in the field at the same time, which enabled a direct comparison of the effect of different crop types on soil properties. On the pH experiment, SOM was lowest in the oat crop, which came at the ‘end’ of the 8 course rotation, 4 years after a grass ley, and highest on the grass ley. These differences were also reflected in the soil biological properties, with earthworm counts and microbial biomass (MBC & PMN in particular) also low under the oat crop. The potato crop also had a low earthworm count, but this was likely to be a reflection of the level of soil disturbance associated with seedbed preparations and planting, rather than organic matter input, with both bulk density and penetration resistance also lower under the potato crop.

Similar effects of the potato crop were seen in the long-term crop rotation experiment at Craibstone, with bulk density, penetration resistance and earthworm count the lowest under this treatment, regardless of fertiliser inputs, reflecting the impact of cultivations used to establish the potato crop. Earthworm numbers were also highest in the grass ley of the crop rotation treatment, particularly where no fertiliser had been applied. However, this was not reflected in topsoil organic matter contents which were similar across all treatments. The grass ley also had the highest VESS score (more compact) and lowest PMN content. The main effect of fertiliser applications was on soil nutrient (P and K) status, although there was some evidence that SOM contents were lower where no fertiliser was applied to the potato and barley crops. The lower SOM contents probably reflect lower yields and therefore crop residue returns in the absence of fertiliser. Other studies carried out at Rothamsted have clearly demonstrated the positive impact of higher long-term N fertiliser additions on SOM contents (Johnston *et al.* 2009). Differences in soil nutrient status in the long-term pH experiment also reflected the different fertiliser inputs to the individual crop types (e.g. higher fertiliser rates and the use of FYM for the potato crop).

The absence of an effect of the grass ley on SOM contents at the old rotation experiment is surprising, particularly as the adjacent long-term pH experiment showed increased SOM content on the grass ley treatment. The benefit of converting arable land to permanent grassland on a range of soil properties, and particularly organic matter, is well recognised (Johnston *et al.,* 2009). Conversion to ley-arable cultivation can also provide benefits, resulting from reduced soil disturbance, larger litter inputs and permanent vegetative cover/presence of roots (Ball *et al.* 2005). For example, Johnston *et al*. (2017) found that topsoil SOM levels increased by 0.25% over a 30 year period following the introduction of a 3 year grass ley in a 5 year rotation, compared to continuous arable. Zani *et al.* (2020) reported that increasing the ley time proportion to 30-40% of the rotation (i.e. 3-4 years in every 10 years) increased topsoil carbon contents and aggregate stability relative to continuous arable. Similarly, Jarvis *et al.* (2017) found that higher proportions of ley in the rotation (length of ley varied from 1 to 5 years in a 6 year rotation), improved topsoil SOC, earthworm numbers and soil structure (porosity and bulk density) at a long-term experimental site in Sweden. However, Collier *et al.* (2020) observed very little difference in SOM contents and aggregate stability between arable and ley-arable soils in a survey conducted across 14 farms in southwest England. These authors found a significant relationship between ‘time since tillage’ and SOC stocks and aggregate stability, with sites that had been tilled within the last 3 years (all under arable or ley arable cultivation) having lower stocks and fewer water stable aggregates than those under permanent grassland or woodland.

5.2. Air & Water supply

The majority of soil organisms need good supplies of air and water to survive and function and these properties are controlled by soil porosity. Soil compaction reduces porosity and increases bulk density with impacts on ‘nearly all properties and functions of soil – physical, chemical and biological’ (Batey, 2009). Tillage and drainage are the main methods for alleviating soil compaction and improving the movement of air and water in soils.

5.2.1. Tillage

There are many recognised benefits of minimising cultivation including changes in soil organic matter dynamics, improvement in soil structure and soil biology, alongside cost saving benefits of machinery, fuel and time (Cooper *et al.,* 2021). Improvements in soils are not only due to the lack of disturbance, but also the increase in surface residue cover associated with no till systems (Giannitsopoulos *et al.* 2020). However, increases in weed burden or compaction can arise in no till systems which can require cultivation to resolve.

The experiment at Loddington investigated the effect of cultivating a previously directed drilled field on soil properties. After 1 year of ploughing the long-term direct drill field, only earthworm numbers were adversely affected, with a reduction in total numbers of 40 % on the ploughed compared to the continued direct drilled soil. The impact of regular cultivation on earthworm numbers is a common observation (Pelosi *et al.* 2009; Stroud, 2019). However, there can be considerable seasonal variation in earthworm numbers (Pelosi *et al.* 2009), with soil moisture having a big influence on earthworm abundance (Ivask *et al.* 2006). Dry soils at Loddington in 2020 may therefore explain the absence of any effect of the different tillage treatments on earthworm numbers at this sampling timing following 3 years of contrasting cultivation techniques.

Ploughing, had little effect on other soil properties although VESS assessments suggested that soil structure had deteriorated slightly on the ploughed treatment after 3 years, and SOM levels were also lower (although this difference was not statistically significant).

Project 12 of the SBSH partnership undertook more detailed analyses of soil microbial diversity and functional activity on the treatments (Bussell, 2021) and showed greater microbial functional diversity in the direct drilled treatment compared to the 3 year ploughed treatment. These results suggest that the impact of one year of cultivation on the heavy textured soils is relatively minor, but that after 3 years of annual cultivation SOM and biological activity began to decline. This supports the review of Conant *et al.* (2007) who reported that whilst there are negative impacts of ploughing, a soil that has an occasional tillage event e.g. to control weeds, will not necessarily suffer long-term impacts, as long as the tillage intensity is not increased permanently.

5.2.2. Drainage

The lack of oxygen in soils as a result of prolonged surface waterlogging can have a significant impact on soil physical, chemical and biological properties with implications for crop growth and productivity. Draining and drying waterlogged soils can reverse these impacts to some extent. Balshaw *et al*. (2014) comprehensively reviewed this subject, including an assessment of the effectiveness of different practices for preventing and alleviating damage caused by waterlogging; one of which is to install mole drainage.

There was no effect of improving the drainage by moling the heavy textured calcareous soil at Boxworth on the suite of soil health scorecard properties, or crop performance. Despite this, there is clear evidence from the literature, that waterlogged soils are very sensitive to degradation from farming operations largely due to compaction and erosion, and that crop yields can be severely impaired as a result (Balshaw *et al.,* 2014 Bhogal *et al.,* 2018). Therefore, ensuring that drainage systems are working properly should be a basic site assessment prior to undertaking the soil health scorecard assessments.

5.3. Chemical environment - pH

The influence of pH on crop growth, primarily through its effect on nutrient availability and potential toxicity, is well documented and underpins current liming policies within the Nutrient Management Guide, RB209 and SRUC Technical Note TN656 (Sinclair *et al.* 2014). The benefits of managing pH were clearly seen on the long-term pH experiment at Craibstone where soil extractable K and Mg concentrations were at their highest at pH 6.5-7.0 and lowest at pH 4.5. However, extractable P concentrations were highest at both low and high pH values. This may reflect the low P sorption capacity (PSC) of the non-calcareous and light textured soil (PSC Index 1 for the Countesswell series; SRUC TN668). The optimum pH range for most soil microorganisms is between pH 5 and 8 (Smith & Doran, 1996). The results from Craibstone support this, with MBC, PMN and CO_2-C burst all at their highest values at pH 6.5. Earthworm numbers were also reduced at low pH values.

5.4. Microbial indicators of soil health

A key aim of the SBSH partnership was to improve our understanding of soil biology, how to measure it and interpret the findings. Due to the complexity and diversity of the soil food web, there are multiple methods for assessing soil biological health. For example, Ritz *et al.* (2009) reviewed 183 candidate soil biological indicators for their potential as indicators of soil health. Assessment of the size and activity of the soil microbial biomass is considered to be a key indicator, more sensitive to management changes than measurements of the total soil organic matter content and useful as an ‘early indicator’ of the overall direction of change in the SOM pool (Rice *et al*. 1996; Powlson *et al.* 1987).

It was difficult to draw conclusions about the relative merits of the different microbial indicators measured at the experimental sites in this study. In particular, and how the different indicators compared to one another, as ‘site’ (soil type, climate, management history) had such a big effect on soil properties. However, the lack of correlation between MBC, PMN, CO_2-C burst and the qPCR estimates of bacterial and fungal biomass suggests different aspects or pools of the microbial community were being measured with the different techniques, such that one method could not necessarily be used a proxy for the other. However, all measures showed a clear and similar response to pH and were higher under grassland than arable land. However, CO_2-C burst was also particularly low on sites with calcareous soils (i.e. Terrington, Boxworth and the high pH treatment at Craibstone), which was not seen in the other microbial indicators measured.

5.5. Overall evaluation of the scorecard approach

It is widely recognised that in order to guide soil management decisions, simple metrics of soil chemical, physical and biological properties, with clear links to soil functions and a robust interpretation framework are required (e.g. Bunemann *et al.* 2018). The scorecard provides a method for benchmarking and targeting soils which would benefit from interventions. For example, the results from Craibstone clearly show the importance of correcting soil pH where levels have fallen, to optimise biological functioning and maximise nutrient use efficiency. There has also been considerable debate on defining a ‘critical’ SOM level below which soil functions become impaired (Loveland & Webb, 2003; Lal, 2020), whose measurement can be used to target interventions. The consensus is that a single value is not appropriate, with the scorecard approach taking into account clay content and rainfall region to define typical ranges which can be used to highlight soils below the typical average, or lower than the bottom of the range of values for potential interventions (Griffiths *et al.,* 2018). In the case of the experimental sites, these were identified as the control treatments (no organic material additions) on the light textured soils at Harper Adams and Gleadthorpe, under the oat crop at the ‘end’ of the rotation on the light textured soil at the Craibstone pH trial and under the no fertiliser treatment of the potato and barley crops at the Craibstone rotation trial. Of the soil physical properties evaluated at the sites, VESS was considered to be the most appropriate for inclusion within the scorecard as it assesses the structural condition of the whole of the topsoil. However, changes due to some management interventions (e.g. organic material addition) can be difficult to detect, particularly if the baseline condition is good. It is therefore recommended that use of this assessment is guided by comparing areas of a field which are known to be poor (e.g. gateway/tramline) and good (e.g. hedge) (Griffiths *et al.,* 2018).

Overall, the results from testing the SBSH scorecard approach across a range of management interventions at the long-term experimental sites clearly demonstrate that the suite of measurements included on the scorecard and their benchmark values do identify situations where there may be a potential risk to crop productivity and highlight areas where further investigation is needed to identify appropriate management interventions. An overall assessment of the measures in the scorecard provides a snapshot of soil health that can be used to guide management action. The management interventions evaluated at the sites align with practices associated with ‘conservation’ or ‘regenerative’ agriculture (Giller *et al.* 2021), with a number of the interventions (returning organic materials to soils, keeping soils covered, minimising soil disturbance and including grass leys) recently highlighted as key practices for ‘restoring agricultural soils’ in a Post Note to the UK Government (Post 662, January 2022). The scorecard interpretation of results from the experimental sites showed the expected responses to these practices, i.e., that applying organic materials (bulky ones in particular), including grass leys in the rotation, optimising soil pH and reducing tillage intensity, improve soil health, and that this improvement can be identified using simple indicators such as SOM, pH, nutrients, VESS and earthworms. Moreover, the positive relationship between grain yield and a number of the scorecard properties, particularly organic matter and nutrient status demonstrated a clear link to soil function thereby supporting the use of this integrated set of measures as a soil health scorecard.

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8. Appendices

8.1. Crop quality at the long-term organic material experimental sites

Table 8.1 Nutrient concentrations in harvested plant material (2018)

	Nutrient concentration (% dm)				
Site/treat	**Total N**	**Total P**	**Total K**	**Total Mg**	**Total S**
Harper Adams (WW)					
Control	2.44	0.32	0.42	0.08^{a}	0.15^{c}
FYM	2.35	0.33	0.44	0.09^{bc}	0.14^{a}
Slurry	2.29	0.32	0.44	0.09^{abc}	0.14^{ab}
Green compost	2.41	0.35	0.46	0.09^{c}	0.15^{bc}
Green/food compost	2.38	0.31	0.43	0.08^{ab}	0.15^{abc}
Food-based digestate	2.44	0.32	0.42	0.09^{abc}	0.15^{ab}
P[1]	NS	NS	NS	**0.03**	**0.04**
Gleadthorpe (SBa)					
Control	2.17^{a}	0.32	0.38	0.09	0.13
FYM	3.05^{b}	0.35	0.43	0.10	0.14
Slurry	2.90^{b}	0.34	0.40	0.10	0.14
Green compost	2.86^{b}	0.36	0.43	0.10	0.14
Broiler litter	2.46^{a}	0.34	0.40	0.10	0.13
P[1]	***0.002***	**NS**	***NS***	**NS**	***NS***
Terrington (WW):					
Control	1.88	0.22	0.34	0.09	0.10
FYM	1.71	0.23	0.34	0.08	0.09
Slurry	1.86	0.26	0.37	0.09	0.10
Green compost	1.80	0.22	0.32	0.08	0.10
Green/food compost	1.77	0.22	0.33	0.08	0.10
Food-based digestate	1.77	0.25	0.37	0.09	0.10
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*

[1] Statistical analysis was undertaken using ANOVA (data normally distributed). There were three replicates of each treatment. *NS:* No significant difference (*P*>0.05). Numbers within a column labelled with different letters indicate significant differences between treatments at a site/year (P<0.05 using Duncans multiple range test)

Table 8.2 Nutrient concentrations in harvested plant material (2019)

	Nutrient concentration (% dm)[2]				
Site/treat	**Total N**	**Total P**	**Total K**	**Total Mg**	**Total S**
Harper Adams (POT: 45-65mm)					
Control	0.34	0.07^{c}	0.31^{a}	0.02	0.034^{b}
FYM	0.29	0.06^{b}	0.44^{d}	0.02	0.026^{a}
Slurry	0.31	0.06^{b}	0.41^{bcd}	0.02	0.029^{a}
Green compost	0.32	0.06^{b}	0.39^{bc}	0.02	0.029^{a}
Green/food compost	0.28	0.05^{a}	0.43^{cd}	0.02	0.025^{a}
Food-based digestate	0.29	0.06^{b}	0.37^{b}	0.02	0.028^{a}
P[1]	*NS*	***0.001***	***0.001***	*NS*	***0.03***
Gleadthorpe (SBa)					
Control	1.28^{a}	0.32^{a}	0.40	0.40	0.09
FYM	1.60^{b}	0.33^{a}	0.42	0.10	0.10
Slurry	1.51^{b}	0.32^{a}	0.42	0.11	0.10
Green compost	1.49^{b}	0.33^{a}	0.43	0.11	0.10
Broiler litter	1.61^{b}	0.37^{b}	0.44	0.12	0.10
P[1]	**0.007**	***0.01***	*NS*	*NS*	*NS*
Terrington (SB)	**Sugar (%)**		**Amino N (mg/100g)**		
Control	17.6		12.3		
FYM	18.0		12.3		
Slurry	18.2		9.7		
Green compost	17.7		12.7		
Green/food compost	17.9		12.3		
Food-based digestate	17.5		13.3		
P[1]	*NS*		*NS*		

[1] Statistical analysis was undertaken using ANOVA (data normally distributed). There were three replicates of each treatment. *NS:* No significant difference (*P*>0.05). Numbers within a column labelled with different letters indicate significant differences between treatments at a site/year (P<0.05 using Duncans multiple range test)

[2] Potato nutrient contents expressed as a % of fresh material

Table 8.3 Nutrient concentrations in harvested plant material (2020)

	Nutrient concentration (% dm)				
Site/treat	**Total N**	**Total P**	**Total K**	**Total Mg**	**Total S**
Harper Adams (SBa)[2]					
Control	2.08^{a}	0.28	0.39	0.91	0.13
FYM	1.86^{a}	0.30	0.43	0.89	0.12
Slurry	1.92^{a}	0.27	0.41	0.88	0.12
Green compost	2.09^{a}	0.28	0.41	0.93	0.13
Green/food compost	1.99^{a}	0.28	0.41	0.92	0.12
Food-based digestate	1.93^{a}	0.29	0.42	0.92	0.12
P[1]	*0.04*	*NS*	*NS*	*NS*	*NS*
Gleadthorpe (WW)					
Control	2.29^{ab}	0.25^{a}	0.35^{a}	0.09	0.13
FYM	2.36^{b}	0.29^{b}	0.38^{b}	0.10	0.12
Slurry	2.38^{b}	0.27^{b}	0.35^{a}	0.09	0.12
Green compost	2.38^{b}	0.28^{b}	0.38^{b}	0.10	0.12
Broiler litter	2.20^{a}	0.27^{b}	0.35^{a}	0.10	0.12
P[1]	***0.02***	***0.02***	***0.007***	*NS*	*NS*
Terrington (WW):					
Control	1.92	0.20	0.28	0.08	0.12
FYM	2.20	0.23	0.29	0.08	0.12
Slurry	1.83	0.21	0.28	0.08	0.12
Green compost	1.95	0.21	0.28	0.09	0.12
Green/food compost	1.91	0.21	0.28	0.08	0.12
Food-based digestate	1.82	0.20	0.28	0.08	0.12
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*

[1] Statistical analysis was undertaken using ANOVA (data normally distributed). There were three replicates of each treatment. *NS:* No significant difference (*P*>0.05). Numbers within a column labelled with different letters indicate significant differences between treatments at a site/year (P<0.05 using Duncans multiple range test)

[2] Although there was a statistically significant (P<0.05) difference in grain N concentrations, the differences were not large enough to be separated by the post hoc Duncans multiple range test.

8.2. Crop quality at Loddington and Boxworth

Table 8.4 Nutrient concentrations in harvested plant material at the Loddington tillage experiment (2018-2020)

Treatment (& harvest year)	**Nutrient concentration (% dm)**				
	Total N	**Total P**	**Total K**	**Total Mg**	**Total S**
2018 (Winter wheat)					
Plough	1.44	0.23	0.37	0.08	0.09
Direct Drill	1.35	0.22	0.34	0.08	0.09
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*
2019 (Winter oats)					
Plough	1.82	0.33	0.30	0.09	0.14
Direct Drill	1.81	0.33	0.31	0.09	0.14
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*
2020 (Spring wheat)					
Plough	1.73	0.32	0.38	0.11	0.12
Direct Drill	1.67	0.31	0.38	0.11	0.11
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*

[1]Statistical analysis was undertaken using a t test. There were three replicates of each treatment. *NS:* No significant difference (*P*>0.05).

Table 8.5 Nutrient concentrations in harvested plant material at the Boxworth drainage experiment (2018-2020)

Drainage treatment (& harvest year)	**Nutrient concentration (% dm)**				
	Total N	**Total P**	**Total K**	**Total Mg**	**Total S**
2018 (Winter barley)					
Un-improved	1.48	0.29	0.48	0.10	0.09
Improved	1.51	0.29	0.47	0.10	0.09
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*
2019 (Spring barley)					
Un-improved	1.32	0.24	0.35	0.07	0.10
Improved	1.26	0.23	0.34	0.07	0.10
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*
2020 (Spring barley)					
Un-improved	1.48	0.29	0.48	0.10	0.09
Improved	1.51	0.29	0.47	0.10	0.09
P[1]	*NS*	*NS*	*NS*	*NS*	*NS*

[1]Statistical analysis was undertaken using a t test. There were three replicates of each treatment. *NS:* No significant difference (*P*>0.05).

8.3. Crop quality at Craibstone pH experiment

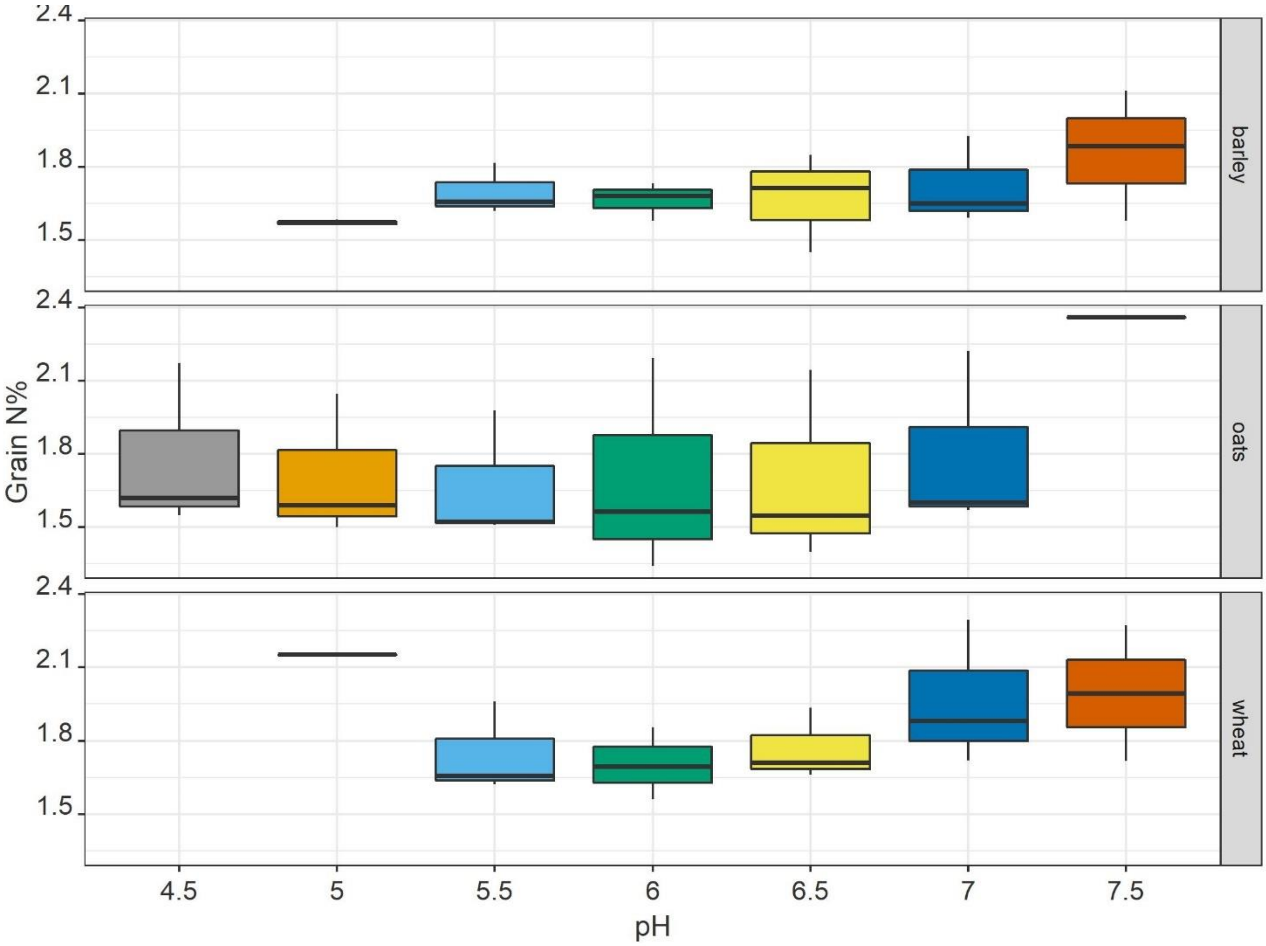

Figure 8-1 Average grain N concentrations (2002-2007) recorded on the cereal crops at the Craibstone pH trial (K. Topp, pers, comm).

8.4. Relationship between microbial indicators

Table 8.6 'Goodness of fit' (R^2) values for the relationship between soil microbial indicators at each of the experimental sites; all relationships were positive unless otherwise indicated (-)

Site	Number of samples	Microbial indicator	MBC	CO_2-C	PMN
Loddington	6	Bacteria (16S)	**0.86**	**0.83**	**0.73**
		Fungi (18S)	0.36	0.45	0.38
		PMN	**0.72**	0.74	
		CO_2-C	**0.78**		
Craibstone pH	48	Bacteria (16S)	0.02	0.02	0.29
		Fungi (18S)	0.04	0.03	0.03
		PMN	0.24	0.04	
		CO_2-C	0.12		
Craibstone rotation	24	Bacteria (16S)	0.04	0.02	0.05
		Fungi (18S)	0.05 (-)	0.01 (-)	0.10
		PMN	0.24 (-)	0.00	
		CO_2-C	0.00		
Boxworth	6	Bacteria (16S)	0.18	0.40	0.19
		Fungi (18S)	0.02	0.27 (-)	0.66 (-)
		PMN	0.10	0.63	
		CO_2-C	0.00		
Gleadthorpe	15	Bacteria (16S)	0.20	0.31	0.18
		Fungi (18S)	0.01	0.16	0.00
		PMN	0.17	0.10	
		CO_2-C	0.27		
Harper Adams (2020 sampling)	9	Bacteria (16S)	0.02	0.41	0.05
		Fungi (18S)	0.01	0.29	0.00
		PMN	0.07	0.25	
		CO_2-C	0.28		
Terrington	9	Bacteria (16S)	0.06	0.36	0.08
		Fungi (18S)	0.00	0.20	0.13
		PMN	0.01	0.27	
		CO_2-C	0.33		