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Soil Biology and Soil Health Partnership Project 2: Selecting methods to measure soil health and soil biology and the development of a soil health scorecard

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CONTENTS

1. Abstract

This project is part of a suite of 11 integrated projects (Soil Biology and Soil Health Partnership) specifically aimed at addressing the AHDB and BBRO Soils Programme call - "Management for Soil Biology and Soil Health". This project is designated Project 2 within WP1 (Benchmarking and Baselining). The purpose of this project is to select methods to measure soil health and soil biology and use these in the development of a soil health scorecard. To achieve this a list of 45 of the most relevant biological, physical and chemical indicators for soil health were compiled. These had been studied in a range of recent reviews as well as the AHDB funded Great Soils project (CP107b). All the indicators were thought initially potentially suitable for use as guides to the health of a soil. These indicators were then scored using a logical sieve approach by both the project partners and the project steering committee to ensure an objective outcome. The criteria used considered relevance to both agricultural production and environmental impact with practical aspects including sample throughput; sample storage; necessity of single or multiple visits for sampling; ease of use; ease of interpretation; sensitivity; cost; standardisation and UK availability of analysis. We were thus able to reduce the potential list of indicators to 12 (including pH, routine nutrients, loss-on-ignition, microbial biomass, respiration, nematodes, earthworms, Visual Evaluation of Soil Structure (VESS), bulk density, water infiltration) that would be used, in conjunction with Workpackage 2 (in-field measurements of soil health) to develop a soil health scorecard during the Programme. The practical results from projects 4, 5, 6 and 7 and the industry interaction within projects 8 and 9 will be used to validate and optimise the scorecard. A provisional scorecard was developed that used a ‘traffic light’ system to give a visual overview of the status of each indicator. So, green – amber – red representing low – moderate – high risk of reduced yield and sub-optimal soil conditions. The scorecard then provides a detailed explanation of the threshold values that delineate the categories. Finally we recommend that the indicator results be benchmarked for comparison over time and across pedoclimatic zones. The provisional scorecard was presented at a technical workshop and two industry workshops. Feedback from those workshops will be carried forward to Workpackage 3, where it will be used to update the scorecard to maximise awareness amongst growers and consultants.

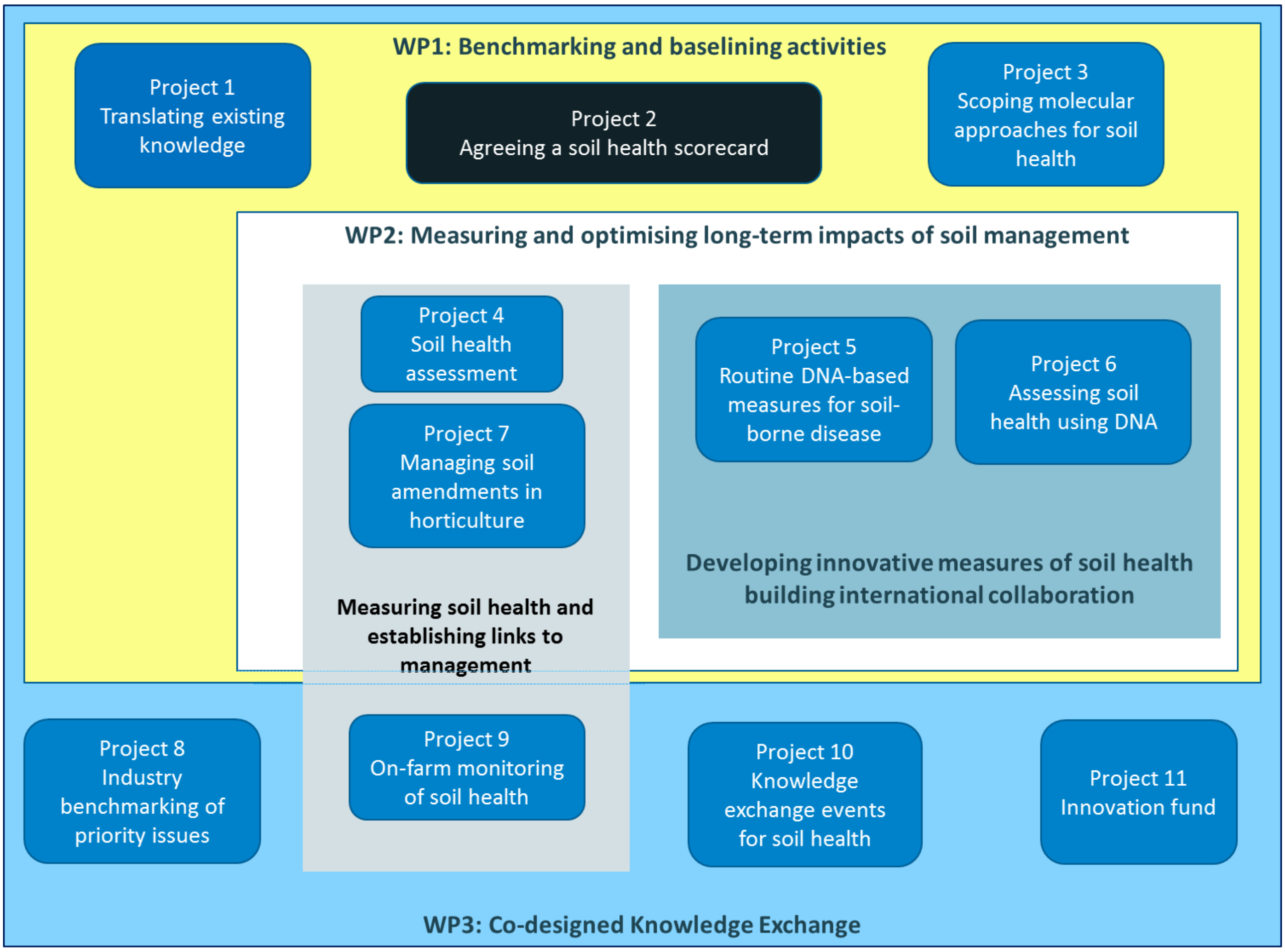


Figure 1. Diagram to show how project 2 (in black) fits into the organisation of the Soil Biology and Soil Health Partnership.

2. Identification of likely potential indicator methods for soil health in UK agriculture

Taking into account published records of soil health testing, most of which also contributed to the literature review carried out as part of Project 1, and the results of the AHDB Great Soils project, a list of 45 measures related to soil health were identified. These covered physical, chemical and biological indicators as an integrated assessment is necessary to give a complete view of soil health.

Physical

- Aggregate stability
- Available water capacity (max amount of plant available water a soil can provide) (AWC)
- Bulk density
- Depth of soil
- Infiltration rates
- Particle density
- Penetrometer resistance
- Permeability – possibly only subsoil as the topsoil permeability is so dynamic
- Porosity/Water filled pore space (WFPS)
- Rate of erosion
- Sealing
- Soil texture
- Shear strength (a measure of soil strength)
- Stoniness
- Visual Evaluation of Soil Structure (SRUC method for visual estimation of soil structure) (VESS)
- Visual Soil Assessment (New Zealand method for visual estimation of soil structure) (VSA)
- Water content at time of sampling
- Water retention characteristic (relation between water content and water potential) (WRC)

Chemical

- CEC (cation exchange capacity – capacity of soil to retain cations)
- C:N ratio
- EC (electrical conductivity – available ions)
- Extractable S
- Extractable Ca

- Heavy metals
- Hot Water Extractable Carbon (HWEC)
- Light fraction organic matter (LFOM)
- LOI (loss on ignition)
- pH
- Potentially mineralisable N (PMN)
- Routine nutrients (P, K, Mg)
- Soil C
- Total Nitrogen

Biological

- Bait Lamina assay (simple measure of biological activity with depth in top 8cm)
- Basal respiration (resting biological activity)
- Earthworms
- Enzyme assays (functional measure of potential activity of C, N P cycling enzymes)
- Functional gene abundance (DNA measure of quantity of the actual enzymes)
- Key pathogens
- Metabolic quotient (respiration per unit biomass – how stressed the microbes are)
- Microarthropods (community structure correlates with ecological health of the soil)
- Microbial biomass (total amount of microbes in soil)
- Microbial community structure/diversity of Bacterial, fungal and archaeal communities
- Mycorrhizal root colonisation
- Nematodes (indices based on community structure correlates with ecological health of the soil)
- Total fungi and bacteria

3. Review of the short-list using a logical sieve approach

The prospective indicators were then ranked using a logical sieve approach as pioneered by Ritz et al. (2009), Stone et al. (2016) and Griffiths et al., (2016). The indicators were rated according to how closely they matched criteria important in three broad categories for indicators of sustainability in agricultural soils. Firstly, they needed to be relevant to both agricultural production and environmental impact. Secondly, they clearly needed to be relevant to agricultural soils (i.e. an indicator only applicable to forests, such as tree trunk diameter, would be no use in this context). Thirdly, they were rated for their practical capabilities for: sample throughput; sample storage; necessity of single or multiple visits for sampling; ease of use; understandability of results (i.e. whether the indicator can easily be used to explain issues of soil health); ease of interpretation (i.e. the score can easily be translated into management options); sensitivity; cost; standardisation and UK availability. The layout of the scoring sheet with the headings and possible scores is shown in Table 1. Scoring sheets were sent to each project partner, associated project partner and members of the Partnership Management Group. The total score for each potential indicator was calculated as the sum of A x B x C and each individual scorecards. The results were then ranked within the physical, chemical, biological categories. Finally, the number of times each of the prospective indicators were ranked in the top 5 highest scoring indicators was added up to give a final score. These final scores are shown in Table 2.

Table 1. The scoring sheet sent to each project partner and associate partner and Partnership Management Group member. Prospective indicators were scored (possible scores are shown as combinations of 0, 1, 2 and 3, where 0 or 1 is no or least relevance, applicability or practicality and 2 or 3 is moderate or highest) and then calculated for each prospective indicator as (sum A) x (sum B) x (sum C).

	A: Relevance to:			B: Applicability to:		C: In practice:											
	Crop production	Environmental Impact		Agricultural soils		Throughput	Storage	single visit	Ease of use	Understandability	Interpretation	Availability	Reproducability	Sensitivity	Cost	Standardised	UK capability
Possible scores	1,2,3	1,2,3		1, 3		1,2,3	0,1,3	1, 3	1,2,3	1,2,3	1,2,3	0,1, 3	1,2,3	0, 2,3	1,2,3	1,2,3	0,1,3
Physical																	
texture																	
stoniness																	
water content																	
Vess																	
VSA																	
Bulk density																	
Penetrometer																	
available water capacity																	
shear strength																	
aggregate stability																	
water retention characteristic																	
rate of erosion																	
depth of soil																	
sealing																	
infiltration rate																	
particle density																	
permeability																	
porosity																	

Chemical																	
pH																	
routine (P, K, Mg)																	
hot water extractable C																	
potentially mineralisable N																	
LOI																	
Light fraction organic matter																	
total N																	
CEC																	
EC																	
C:N ratio																	
total C																	
heavy metals																	
extractable S																	
extractable Ca																	
Biological																	
Microbial biomass																	
Basal respiration																	
metabolic quotient																	
nematodes																	
microarthropods																	
earthworms																	
bait lamina strips																	
enzyme assays																	
functional gene abundance																	
key pathogens																	
mycorrhiza root colonisation																	
total fungi and bacteria																	
species diversity																	
bacteria/fungi/archaea																	

Table 2. Scores (i.e. number of times each of the prospective indicators were ranked in the top 5) obtained for each of the prospective indicators from the logical sieve. The indicators are described in more detail in the text in Section 2 above.

Physics		**Chemistry**		**Biology**	
Bulk density +	8	pH +	11	Microbial biomass +	8
Soil texture	7	Routine Mg,K,P +	8	Nematodes	6
Water content	6	Loss-On-Ignition +	8	Microarthropods	6
VESS +	6	Total C	6	Earthworms +	6
VSA	5	Total N	4	Respiration +	5
Penetrometer +	5	C:N	3	Key pathogens	5
AWC	5	PMN	3	Metabolic quotient	4
Porosity	4	Ca	3	Bait lamina	3
Soil depth	3	HWEC	2	Functional genes	3
Infiltration	3	CEC	2	Mycorrhiza	3
Aggregate stability	2	S	2	Total fungi & bacteria	2
Stoniness	1	Heavy metals	1	Microbial diversity	2
Water Retention Character	1	Light Fraction OM	1	Enzyme assays	1
Shear strength	0	Electrical Conductivity	1	DNA measures*	n/a
Erosion	0				
Sealing	0				
Particle density	0				
Permeability	0				

- n/a, not applicable for the scorecard because although their potential is recognised and they are being tested in workpackage 2, they are not yet at a stage ready for deployment.

+ selected for initial inclusion on the scorecard

The scorecard aims to capture the interactions between physics, chemistry and biology that underpin soil health in a concise and practical format for the user and also to provide useful information to inform management. Hence at least three of the top ranked indicators from each category were chosen for inclusion on the scorecard (indicated by + in Table 2). Soil texture is a fundamental property that is not changed by management and is, therefore, not appropriate as an indicator to monitor changes in soil health. However, an underpinning knowledge of soil texture is needed to benchmark the values obtained for the indicators appropriately – see Section 4. Thus from the physical category we have taken bulk density, VESS and penetrometer resistance. Water content (at time of sampling) was not included in the scorecard as it largely depends on the immediately preceding weather. Many of the chemical indicators are in common use in commercial soil analyses, which probably explains the clear preference for pH, routine nutrients and Loss-On-Ignition.

Biological indicators have been the least used to date and so there is less of a clear cut picture than for the chemical indicators, hence more of these indicators are included for testing and development within Workpackage 2 (Table 3). We propose to use microbial biomass, one of nematodes, microarthropods or earthworms (depending on the results from Workpackage 2) and respiration measured on an incubated sample (Solvita currently delivered commercially by NRM). The latter indicator was selected given the practical consideration at present that it is easier to measure than key pathogens, although the pathogens are the subject of developmental work in Project 5 within the Programme.

Table 3. Summary of the ways in which soil indicators will be used / developed within the programme.

Soil indicator	Use of indicator within the Programme
pH	Relatively common indicators will be included
Routine nutrients (extractable P, K, Mg)	
Bulk density	
Penetrometer resistance	
Visual evaluation of soil structure (VESS)	Less common indicators evaluated and framework for interpretation will be developed
Loss on ignition (soil organic matter)	
Respiration (Solvita test, NRM)	
Earthworms	
Microbial biomass C	New indicators developed and tested in Projects within workpackage 2
Potentially mineralisable N	
Total N	
Nematodes	
Microarthropods	
DNA measures (including pathogens)	

4. Creating an integrated soil health scorecard and interpretation framework

The framework used for communication of information about indicator values to farmers / growers is based on proposals for soilquality.org.uk, which is itself based on the Australian model (http://www.soilquality.org.au/) developed through farmer engagement, supported by grower group and levy funding (GRDC). The soilquality.org.uk framework has been developed and is being tested as part of a Sustainable Agriculture Research and Innovation Club funded project (2016-2019). This collaboration enables the Programme to use a wider database for benchmarking and ultimately more relevant advice. Results for each of the soil health test indicators will be presented as an analytical value with management advice together with a 'traffic light' system, whereby a result in green indicates a typical or optimum result (Figure 2). Amber and red categories would indicate the need for further examination (perhaps by more detailed sampling) and, in many instances, management intervention to maintain best soil condition. The traffic light system represents either a comparison to a 'norm' e.g. for soil organic matter or earthworms, or is linked to a directly measured negative effect e.g. pH, nutrients:

RED (High risk, need to investigate urgently)	Management advice would be given for red and amber results
AMBER (Moderate risk, need to investigate further)	
GREEN (Low risk, continue to monitor)	

Figure 2. The traffic light system proposed for communication alongside indicator values

4.1. Categories and traffic lights for the potential indicators

Based on a review of the literature, including grey literature and consultation with agronomists and advisors the following traffic lights have been proposed. Some initial discussion about indicator frameworks took place with academics and industry in a SARIC project workshop for soilquality.org.uk in March 2017 and the frameworks discussed and agreed there (pH, P, K, Mg, VESS and for England only, OM) have been adopted with some modification where appropriate. The categories and traffic lights will be evaluated within field trials in Projects 4 and 7 of the programme. For each of the indicators, we present the proposed grouping "classes" that would be used for presentation e.g. in bar charts of the data distribution, the associated traffic light colour and any further note / description.

4.1.1. pH (measured in water)

The groupings and traffic lights have been set with reference to the categories used by the Professional Agricultural Analysis Group (PAAG) and production-based information – Nutrient Management Guide RB209, SRUC Technical notes.

Bar chart classes	Traffic light colour	Any additional description of this class (e.g. toxic)
< 5.0		Potential problems with aluminium toxicity, nutrient availability
5.0 – 5.49		Potential problems with aluminium toxicity
5.5 - 5.99		
6.0 - 6.49		Amber (cropping), perhaps use Green (grass)
6.5 - 6.99		
7.0 - 7.49		
7.5 - 7.99		Potential nutrient interaction issues
> 8.0		Potential nutrient interaction issues

4.1.2. Routine nutrients (P, K, Mg)

The analytical approach and interpretation frameworks used in Scotland and England are different; hence two sets of scales are needed. The groupings and traffic lights have been set with reference to the categories used by the Professional Agricultural Analysis Group (PAAG) and production based information – Nutrient Management Guide RB209, SRUC Technical notes.

Extractable P

The environmental risk from soil movement as sediment, especially for P is also taken into account. Some further work has been carried out in Scotland on the role of P sorption by soils; hence any accompanying factsheet would give information about sorption capacity and how this might affect availability of extractable P. In addition, any supporting materials would include the findings of recent AHDB-funded work on soil P including “Cost-effective phosphorus management on UK arable farms” (Rollett et al., 2017).

Scotland – Extractable P (Modified Morgan's) mg/L

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
0 - 1.7	Red	VL – risk to production
1.8 - 4.4	Amber	L – potential risk to production
4.5 - 9.4	Green	M-
9.5 - 13.4	Green	M+ Application of organic manures still recommended as a supply of other nutrients but generally no requirement for additional fertiliser P
13.5 - 30.0	Amber	H – potential risk to environment
> 30.0	Red	VH – risk to environment

England – Extractable P (Olsen) mg/L

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
0 - 9	Red	Index 0 – risk to production
10 - 15	Amber	Index 1 – potential risk to production
16 - 25	Green	Index 2
26 - 45	Green	Index 3 – potential risk to environment, but P required for P-responsive crops including potatoes, maize and some vegetable crops. Application of organic manures still recommended as a supply of other nutrients but generally no requirement for additional fertiliser P
46 - 70	Amber	Index 4 – potential risk to environment.
> 71	Red	> Index 4 – risk to environment

Extractable K

While target maintenance indices are different for sands (i.e. L or Index 1), this is still a level that is considered a potential risk to production and hence amber for presentation. There is no recognised environmental risk for K.

Scotland – Extractable K

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
0 - 39	Red	VL – risk to production
40 - 75	Amber	L – potential risk to production
76 - 140	Green	M-
141 - 200	Green	M+
201 - 400	Green	H – no expected benefit of fertiliser K
> 400	Green	VH – no expected benefit of fertiliser K

England – Extractable K

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
0 - 60	Red	Index 0 – risk to production
61 - 120	Amber	Index 1 – potential risk to production
121 - 180	Green	Index 2-
181 - 240	Green	Index 2+
241 - 400	Green	Index 3
> 400	Green	> Index 3 – no expected benefit of fertiliser K

Extractable Mg

Groupings and traffic lights also take account of the impact of high Mg levels in terms of nutrient interactions in medium/heavy soils, which are the only soil type in which such high values are expected to occur.

Scotland – Extractable Mg

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
0 - 19	Red	VL – risk to production
20 - 60	Amber	L – potential risk to production
61 - 200	Green	M-
201 - 1000	Green	H
> 1000	Amber	VH - potential nutrient interaction issues

England – Extractable Mg

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
0 - 25	Red	Index 0 – risk to production
26 - 50	Amber	Index 1 – potential risk to production
51 - 100	Green	Index 2
101 - 175	Green	Index 3
176 - 250	Green	Index 4
251 - 350	Green	Index 5
> 350	Amber	> Index 5 - potential nutrient interaction issues

4.1.3. Visual Assessment of Soil Structure - VESS

The SRUC VESS (arable) and Healthy Grassland Soil methodology is recommended here; these are slightly different methods for arable and grassland but same 1-5 scoring system.

Bar chart classes	Traffic light colour	Any additional description of this class (e.g. toxic)
5		Poor; needs management action
4		Poor; consider management action
3		Moderate
2		Good
1		Good

Here the accompanying information to guide sampling is very important – badly selected sample points will mean that the data has very little value. We therefore suggest that though the score recorded should be for a representative "mid-field" site; nonetheless the farmer should be guided to make their own comparison with an area known to be poor (gateway) and good (hedge). The linking of physical and chemical measures directly here is perhaps the most novel aspect of this approach in comparison with existing approaches to soil sampling on farm. Therefore there will need to be some good supporting information to help farmers see the value of the integrated sampling approach as it will cost more time (and hence money) at the sampling step. At the piloting stage, it will therefore be critical to explore this with the participating farmers.

Any accompanying factsheet will need to make clear the links to other systems such as VSA (drop–shatter test).

4.1.4. Soil Organic Matter (measured as % Loss-On-Ignition – LOI)

There are no existing thresholds given for soil organic matter or soil organic C in the public domain. However, there are a number of projects that have reviewed work on soil organic matter and critically assessed opportunities to set/ communicate target values to farmers (especially Defra projects SP0306 and SP0310). We describe the approach we have taken to derive thresholds for testing within the Programme, below. There is currently no recommended approach for Northern Ireland, though it should be possible to draw from work carried out by Teagasc for Ireland, along with the work below to develop categories and traffic lights for testing.

England and Wales

The Defra projects covered England and Wales only. The final reports for SP0306 and SP0310 are available and although the findings are complex, it is possible to draw out typical ranges and also indicate values where it is appropriate to consider that there may be a risk to production (amber, red). These ranges also require land use, climate and topsoil texture to be taken into account.

The approach used the background information from SP0306 to set the context.

- In SP0306, the project team critically assessed the literature with regard to critical values for a range of soil functions directly and indirectly affected by soil organic matter and concluded that "as long as returns of fresh or active OM to the soil are adequate, then soil (function) is not compromised by a reduction of total SOM below 2% total organic carbon". This value is the old "rule of thumb" target which has been often extracted from Greenland et al. (1975) (equal to c. 3.5 % SOM (LOI)).
- They suggested that, "if there is a critical threshold, it is closer to 1% total organic carbon" and that impacts on function, especially structural stability, will most often be seen in light soils (this limit would equate to < 1.72% OM (LOI)).
- They identified a difference between light and medium/heavy soils in terms of their ability to stabilise OM and hence used the representative soil survey and modeling approaches to investigate the long-term OM content of soils. They concluded that even with no new OM inputs, soil organic matter would be expected to be higher, and above the critical threshold, in medium /heavy soils (>18% clay) = 2.3% total organic carbon than in light soils = 1.3% total organic carbon.

The work done in SP0310 (which built on SP0306 – but with a different research team) gives good information on economic benefits and farmer perceptions that can be used to underpin the development of any supporting information for farmers.

- They investigated the factors controlling soil organic matter contents (as %SOC) using multiple regression analysis of the 1980 England and Wales National Soil Inventory.
- Indicative soil organic carbon ranges were identified for arable & ley/arable systems (with some comparison with lowland permanent grassland) grouping the land units by clay content (10% classes from 0 - 50%) and climate by rainfall (3 groups – low (< 650 annual average precipitation mm), mid (650 – 800), high (800 -1100))
- Robust statistics were used so that the outliers could be handled appropriately – full details are published in Verheijen et al. (2005). This uses the median and statistical estimator, Qn, which is an alternative to the standard deviation to describe the data distribution.

Hence, the relationships obtained in SP0310 were re-drawn and the median and 80% confidence intervals for Qn were determined for the simplified cross-compliance topsoil texture class groups. They are presented in Table 4 for the same rainfall groups as used in SP0310, however, these are then further allocated by the Met. Office climate regions. Upland categories would need to be added in some regions.

Table 4. Interpolated values for "indicative SOC management ranges" using the interpretation approach and derived from the data presented in Verheijen et al. (2005).

		As SOC%			As SOM (LOI) %		
		Light	Medium	Heavy	Light	Medium	Heavy
Clay content		<18%	18-35	>35%	<18%	18-35	>35%
Low rainfall	Upper	1.9	2.9	3.8	3.3	5.1	6.6
	Median	1.3	2.0	2.6	2.2	3.4	4.5
	Lower	0.7	1.0	1.3	1.1	1.8	2.3
Mid rainfall	Upper	2.5	3.5	4.5	4.2	6.1	7.7
	Median	1.6	2.4	3.1	2.7	4.1	5.3
	Lower	0.6	1.2	1.6	1.1	2.0	2.8
High rainfall	Upper	3.6	4.4	5.2	6.2	7.6	8.9
	Median	2.2	3.0	3.6	3.8	5.1	6.3
	Lower	0.8	1.5	2.1	1.4	2.6	3.7
Permanent pasture – all climates	Upper	4.6	5.4	6.1	7.9	9.3	10.5
	Median	2.9	3.7	4.4	5.0	6.4	7.6
	Lower	1.3	2.1	2.7	2.2	3.5	4.7

It is suggested that the ranges are indicatively grouped so that data is considered

Very low for the climate / soil type (lower than lower range in the table)

Lower than average (between the lower limit and the median)

Target (Between the median and the upper range)

Very high for the climate / soil type (above the upper range)

England and Wales – Cropping - low rainfall = E England

Bar chart classes	**Light**	**Medium**	**Heavy**
<1			
1 - 2			
2 - 3	Target		
3 - 4	High	Target	
4 - 5	High	Target	Target
5 - 6	High	High	Target
6 - 7		High	High
7 - 9		High	High
> 9			High

England and Wales – Cropping - mid rainfall = NE England, Midlands, S England

Bar chart classes	**Light**	**Medium**	**Heavy**
<1			
1 - 2			
2 - 3			
3 - 4	Target		
4 - 5	High	Target	
5 - 6	High	Target	Target
6 - 7	High	High	Target
7 - 9		High	High
> 9			High

England and Wales – Cropping - high rainfall = SW England, NW England

Bar chart classes	**Light**	**Medium**	**Heavy**
<1			
1 - 2			
2 - 3			
3 - 4			
4 - 5	Target		
5 - 6	Target	Target	
6 - 7	High	Target	Target
7 - 9	High	High	Target
> 9		High	High

England and Wales – Grassland – all climates (N.B. lowland)

Bar chart classes	**Light**	**Medium**	**Heavy**
<1			
1-2			
2-3			
3-4			
4-5	Target		
5-6	Target	Target	
6-7	Target	Target	Target
7-9	High	Target	Target
>9	High	High	High

Scotland

Using the JHI Soil Information System database (http://sifss.hutton.ac.uk/SSKIB_Stats.php),

By drawing on a specific location for a sampling site, the Soil Information System identifies the main expected soil series. Hence the thresholds can be related to this detailed and extensive database, providing data that are relevant for each particular soil type and location. The database gives the main soil series and ranges of LOI for each soil series in the form of a box and whisker plot (Figure 3a), from which the thresholds can be generated (Figure 3b).

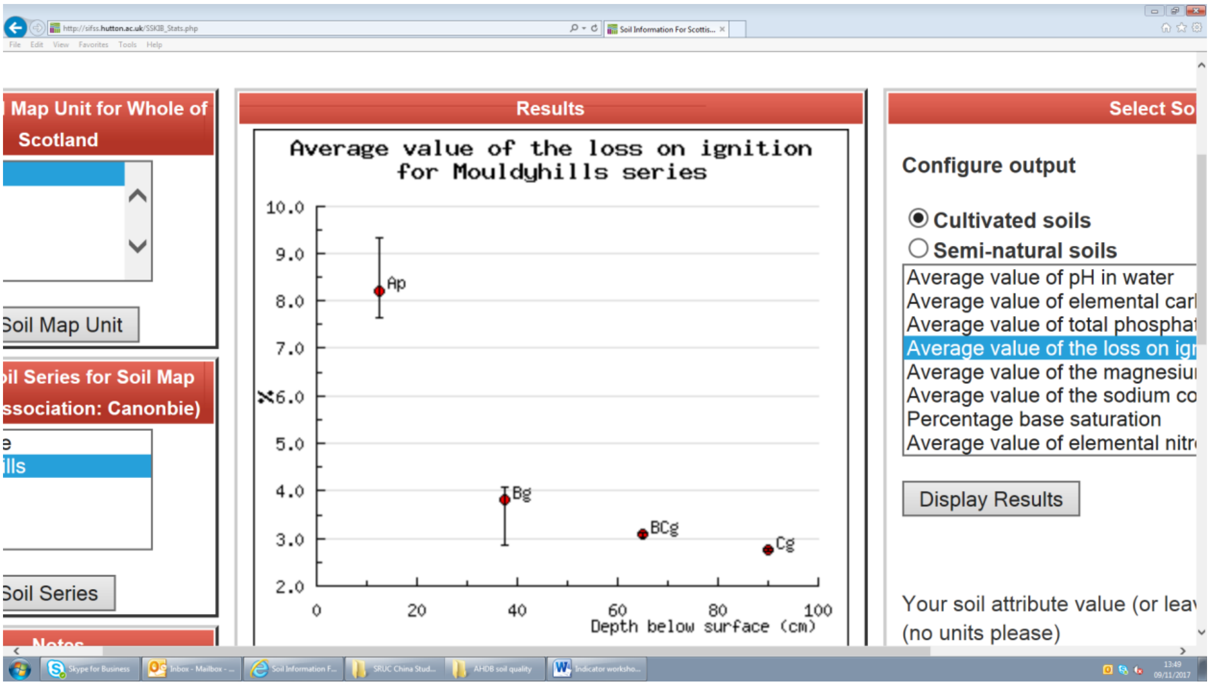


Figure 3a. Example output from the JHI Soil Information System for Mouldyhills series soil, whose cultivated layer of soil has a median %LOI of 8.2% and a lower quartile of 7.6%

LOI class for particular soil series	Traffic light colour	Any additional description of this class (e.g. toxic)
Less than lower quartile		Poor; consider management action
Between lower quartile and median		Moderate
Greater than median		Good

Figure 3b. For each soil series, where data exists the data would then be allocated as above

4.1.5. Microbial Biomass Carbon

Measuring the size of the microbial biomass (typically as the amount of carbon within the microbial biomass, or MBC) has been widely used to assess the impact of environmental or anthropogenic change on soil microorganisms (Gonzalez-Quinones et al. 2011). Activity of the soil microbial biomass regulates organic matter transformations, and associated energy and nutrient cycling, thus in general an increase in MBC is considered beneficial and a decrease detrimental. It has been suggested as a routine measurement for soil monitoring (Carter et al., 1999). There have been several studies showing that MBC, often as part of a suite of soil health measures, correlates positively with crop yield (Lupwayi et al. 2014; 2015; D'Hose et al, 2014; Kiani et al., 2017).

The bulk of the scientific work has relied on the chloroform fumigation-extraction method (Vance et al., 1987). Explained simply this takes two samples of soil, one of which is fumigated with chloroform vapour to lyse all living cells (e.g. bacteria, fungi, nematodes, microarthropods etc.) and release their contents as organic carbon (a complex mixture of proteins, amino acids and other cellular compounds) into the soil. The difference in C content between the fumigated and unfumigated portions of soil is used to calculate the microbial biomass. However, for routine monitoring it is unlikely that chloroform fumigation would be used, for health and safety and other practical considerations. The more practical alternative is the substrate-induced respiration method (Anderson and Domsch, 1978), in which a soil sample is mixed with glucose to stimulate a respiratory burst from the microorganisms in the soil. The amount of CO_2 released is strongly correlated to the MBC as measured by chloroform fumigation.

More recently a CO_2 burst test is being used as a measure of soil health, such as the Solvita test offered by NRM in the UK. Whilst similar in principle to the substrate-induced respiration method, the CO_2 burst test measures in the increased respiration when dried soil is rewetted. This doesn't measure microbial biomass as such, and is more considered a general indicator of soil biological activity (Franzluebbers, 2016; Curtin et al., 2017) more closely related with N mineralization potential. Developmental studies in Projects 4 and 7 will be measuring MBC using both chloroform-fumigation and substrate-induced respiration, in combination with the NRM CO_2 burst test and potentially mineralisable nitrogen.

The suggested values for use in UK soils which will be tested (within Projects 4 and 7) are based on a meta-analysis by Kallenbach & Grandy (2011). In the first instance no separation by land-use, climate or topsoil texture is proposed, as there are insufficient data available to make such a separation. Although it is clear from research data that these are key factors determining the size of the microbial biomass in soil.

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
< 100 ug C / g		
100 - 200		
200 - 400		
400 - 1000		

4.1.6. Bulk Density

Bulk density (Mg/m^3) is a measure of compaction with higher values indicating more compact soil. Root growth may be restricted at high bulk density and trigger values for topsoils with different organic matter content have been identified for the UK (Merrington et al., 2006). This approach may be more complex to apply in practice as it requires cross-linking of the values from two separate indicators.

	Bulk density threshold for:	
Organic Matter Content (%)	**Tilled Land Arable + Ley**	**Untilled Land Permanent pasture and rough grazing**
Mineral Soils		
<2	>1.60	>1.50
2 - 3	>1.50	>1.40
3 - 4	>1.40	>1.35
4 - 5	>1.30	>1.25
5 - 6	>1.25	>1.20
6 - 8	>1.20	>1.15
Organic mineral soils	>1.00	

This would only give 2 categories, bad (i.e. red) above the threshold and good (i.e. green) below the threshold. It would be more useful to indicate bulk densities that are bordering on the threshold and so identify soils that may need some management intervention to keep them from degrading any more. A value of 10% of the threshold would give the following table:

	Bulk density threshold for:					
	Tilled Land Arable + Ley			Untilled Land Permanent pasture and rough grazing		
%OM	Good	Moderate	Poor	Good	Moderate	Poor
<2	1.44	1.44-1.6	1.6	1.35	1.35-1.5	1.5
2 - 3	1.35	1.35-1.5	1.5	1.26	1.26-1.4	1.4
3 - 4	1.26	1.26-1.4	1.4	1.215	1.215-1.35	1.35
4 - 5	1.17	1.17-1.3	1.3	1.125	1.125-1.25	1.25
5 - 6	1.125	1.125-1.25	1.25	1.08	1.08-1.2	1.2
6 - 8	1.08	1.08-1.2	1.2	1.035	1.035-1.15	1.15
>8	0.9	0.9-1.0	1.0	0.9	0.9-1.0	1.0

4.1.7. Penetrometer resistance (maximum value in top 30 cm)

There is consensus that a penetrometer resistance greater than 2 MPa will significantly impede root growth, when measured at or near field capacity. A survey by MAFF (Ministry for Agriculture, Food and Fisheries, as was) recommended the following categories:): Loose <0.5MPa; Medium 0.5 -1.25 MPa; Dense 1.25 – 2.0 MPa; Very dense >2.0 MPa (MAFF, 1982). Penetrometer resistance in excessively wheeled areas of arable soils were between 2.0 and 2.5 MPa (Ball and O'Sullivan, 1982). 2.5 MPa was an upper limit for cotton taproots to grow through soil, with rooting density reduced at 1.0 – 2.0 MPa (Taylor, 1971), while more recent studies of UK soils found that at >2.0MPa root elongation was slowed to <50% of its unimpeded rate (Valentine et al., 2012).

The variation of penetrometer resistance with soil water content may well prove to be a practical obstacle to implementing this measure as a soil health test, but this will be evaluated from the practical results obtained in Projects 4, 5 and 7 of the Soil Biology and Soil Health Partnership.

Bar chart classes	Traffic light colour	Description of this class (e.g. toxic)
>2.0 MPa		Compact, very dense. Root elongation significantly decreased
1.25 - 2.0 MPa		Firm/partly compact
0.5 – 1.25 MPa		Optimal for root growth
<0.5 MPa		Loose

4.1.8. Earthworms

The earthworm indicator combines information about earthworm numbers and the number of species seen when a 20 x 20 x 20 cm soil block is assessed in the field (Shepherd et al., 2008; Väderstad, 2016). The thresholds in the chart below map closely to those presented by Bartz et al (2013) for Brazilian cropping systems, who suggested 4 categories, namely: poor (<1 earthworm per 20 x 20 cm sample and 1 species); moderate (1-4 and 2-3 spp.); good (4-8 and 4-5 spp.) and excellent (>8 and >6 spp.). Recent meta-analyses have indicated the variation of earthworm abundance and importance with soil texture. In conventionally tilled arable soils average earthworm abundances for light, medium and heavy soils were 2, 1-2 and 2 earthworms per $20cm^2$, which was increased in no-tillage systems to 3 and 9 for light and medium soils respectively, there being no data for no-tillage and heavy soils (van Capelle et al., 2012). Interestingly when analysing the earthworm effect on crop productivity, increases in yield due to earthworms were less in light and medium soils (10 – 20% increase) than in heavy soils (45% increase) (van Groenigen et al., 2014). In the first instance only separation by land use is proposed, as there are insufficient data available to make further separation with regard to climate or topsoil texture, though it is clear from research data that at the extremes these can be important in determining the earthworm community structure and overall numbers.

Bar chart classes Number per 20x20cm spadeful		Traffic light colour	Description of this class
Arable	Grass		
<4	< 15 and predominantly 1 species		Depleted
4-8	15-30 1-2 species		Intermediate
>8	>30 and 3 or more species		Active

4.1.9. Nematodes and micro-arthropods

Current nematode testing relies entirely on the quantification and enumeration of certain plant-feeding nematodes for soils going into specified crops. These are predominantly potato cyst nematode (PCN) and the so-called free-living nematodes (FLN) responsible for virus transmission to crops. This, however, overlooks the fact that there are a range of different nematode feeding types present (such as bacterial-feeders, fungal-feeders, predatory nematodes and omnivorous nematodes, as well as plant-feeding types) and that these nematodes are distributed throughout the soil food web. This fact makes them ideally suited to indicate the biological health of the soil (Ritz and Trudgill, 1999). To do this various ecological indices are used to classify nematode community data (Ferris et al., 2001). The Maturity Index is most widely used but more ecological papers are now using the Enrichment and Structural indices calculated from the types of nematode present (identified by microscope or DNA), which if plotted can position the community in relation to an idealised optimum (Figure 4). The enrichment index reflects the presence of those nematodes that reproduce quickly and respond to high levels of nutrients, generally bacterial-feeders that indicate rapid-nutrient cycling and a surplus of available nutrients. The structure index, on the other hand, reflects the stability and undisturbed nature of the food web as it depends more on the sensitive and relatively long lived predatory and omnivorous species. Best soil health is indicated by a low enrichment index and a high structural index. The scores can then be used to give “traffic lights”. A similar approach could be taken for microarthopods and the data collected in Projects 4 and 7 will be used to test this approach for nematodes and to develop the approach for microarthopods. The use of microarthropods as indicators of soil health is recommended for national soil monitoring (George et al., 2017).

The community analysis reflects the overall composition of the nematodes present, but for certain crops (especially potatoes) there will still be need for the focussed PCN and FLN analyses to indicate likely damage to specific crops.

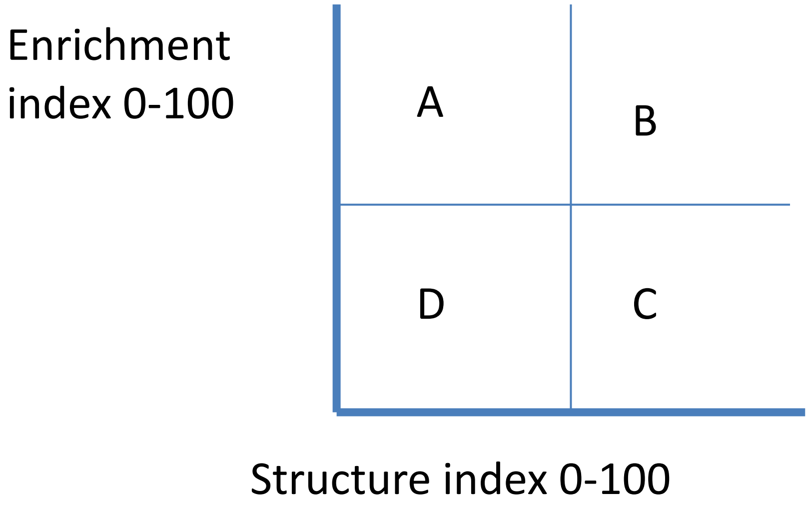
Bar chart classes Enrichment/structure index	Traffic light colour	Description of this class (e.g. toxic)
5		
4		
3		
2		
1		

4.1.10. Soil Health Scorecard

The final design of the soil health scorecard would be in the hands of the company/laboratory undertaking the assessment and would presumably reflect the branding, marketing and aesthetic requirements of the provider. While some the proposed measures can be done in-house by the grower (i.e. earthworms, VESS), the majority require laboratory analysis and the actual layout of the scorecard would be their responsibility.

The overall soil heath scorecard would be summarised in the visual front page 'traffic light' results (Figure 5) and would be followed with links to or hard copy of background information on the parameters measured, and management advice, especially if red or amber. The traffic lights are either threshold values, where there is evidence for agronomic or environmental concerns, or a normal operating range. Thus, in the case of soil P, for example, the categories are well documented in Nutrient Management Guide RB209 (https://ahdb.org.uk/projects/RB209.aspx) and SAC technical notes (https://www.sruc.ac.uk/downloads/120202/technical_notes) and represent values where there are risks to crop production at the lower end of the spectrum and risks of run-off and losses at the upper end of the spectrum. While for earthworms the abundance reflects typically observed values.

We have listed and provided threshold values for 12 soil health parameters. It is unlikely, for cost reasons, that all 12 would actually be used for a practical scorecard. The final recommended list will be depend on the results from Project 4, in which the potential indicators are tested in a range of agricultuiral scenarios. It is likely that the final scorecard would include at least: pH and routine nutrients (as these are typically what a grower has analysed currently) together with LOI, a physical parameter and a biological parameter.



Where
A= a disturbed community, N-enriched, bacterial dominated, low C:N
B = moderately disturbed community, N-enriched, bacterial dominated, low C:N
C = undisturbed community, not enriched, fungal dominated, moderate C:N
D = stressed community, N-depleted, fungal dominated, high C:N

The position within the grid can be turned into scores, where 1 is considered the most healthy and 5 the least healthy community.

5	5	5	5	5	5	5	5
5	4	4	4	4	4	4	4
5	4	3	3	3	3	3	3
5	4	3	2	2	2	2	3
5	4	3	2	1	1	2	3
5	4	3	2	1	1	2	3
5	4	3	2	2	2	2	3
5	4	3	3	3	3	3	3

Figure 4. Outline of the use of the ecological index values (enrichment, structure) for a nematode community observed to assign a score which relates to the health of the overall soil biological community (developed from Ferris et al. 2001)

Soil Analysis – Soil Health Report

Contact name:

Field Type: Semi-permanent grassland

Climate zone: Cool and Wet (England)

Analysis	Result	Units	Management Indication
pH	5.9	----	
Extractable P	60	mg $litre^{-1}$	
Extractable K	140	mg $litre^{-1}$	
Extractable Mg	100	mg $litre^{-1}$	
Loss on Ignition	5.5	%	
Bulk Density	1.25	g cm^{-3}	
VESS	4	score	
Penetrometer resistance	3.0	MPa	
Microbial Biomass Carbon	400	mg kg^{-1}	
Earthworms	19/2	no. $20cm^2$/no. types	

Figure 5. Example of a front page overview, using the indicators selected from the logical sieve approach, for a hypothetical grassland field in England that needs some lime, has had a fair bit of P added and the soil structure is compacted

5. Conclusions

There has been a concentrated effort put into devising practical methods to measure soil health (including soil biodiversity and soil quality) at a UK and a European level. Monitoring soil health is a concern for government at national/ regional scales and also for farmers and land managers who are seeking to maintain and improve soil health at farm and field scale. This project has successfully built upon that work and developed it further by specifically selecting indicators and tailoring the frameworks for interpretation relevant to UK agriculture (grassland, arable, sugar beet, potato and horticultural crops) under UK climatic and soil conditions.

The recommended indicators together provide a soil health scorecard which integrates physical, chemical and biological aspects to give a snapshot overview of soil health akin to an MOT or end of school report. To support management of soil health on farm, the indicator results should be benchmarked for comparison over time and across different pedoclimatic zones. This benchmarking will quickly (1-5 years) gather a body of data from which the normal operating range of those measures not currently routinely measured (i.e. earthworms, microbial biomass, PMN), can be evaluated against soil texture, climate and cropping regime to revise and improve the thresholds and so improve the advice given.

Feedback on the provisional scorecard was presented at a technical workshop and two industry workshops. This is reported separately (Project 8) and further evaluation of the scorecard will continue through the rest of the programme. Project 4 will provide a robust verification of the frameworks for interpretation of indicators and Project 9 will evaluate the scorecard in use on farm with consideration given to all aspects from sampling to data interpretation.

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