GREATSOILS

British Beet BBRO Research Organisation

AHDB

February 2018

Final Report No. 91140002-01

Soil Biology and Soil Health Partnership Project 1: Translating existing knowledge of management effects on soil biology and soil health for practitioners

Bryan S. Griffiths[1], Paul R. Hargreaves[2], Anne Bhogal[3], Felicity V. Crotty[4] and Elizabeth A. Stockdale[5]

[1] SRUC, Crop and Soil Systems Research Group, West Mains Road, Edinburgh, EH9 3JG, UK

[2] SRUC, Dairy Research Centre, West Mains Road, Edinburgh, EH9 3JG, UK

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

[4] GWCT Allerton Project, Loddington House, Loddington, Leicester LE7 9XE, UK

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

This review was produced as the final report of a 12 month project (Project 1) within the Soil Biology and Soil Health Partnership (AHDB: 91140002) which started in January 2017. The work was funded by a contract for £19,017.70 from AHDB and BBRO.

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 1 within WP1 (Benchmarking and baselining, see Figure 1). The purpose of this project is to update the existing scientific reviews of soil biology and soil health, especially as applicable in temperate UK cropping systems and then to translate the information from that scientific format into a descriptive model which allows the important interactions (environmental, soil, crop, management) contributing to soil health to be summarised semi-quantitatively. This will link with the key treatment/soil/ site combinations used in subsequent projects (WP2), to provide the understanding needed to explain the rationale for effective management practices for users. This approach will also allow the development of a visual tool that summarises the key interactions affecting soil biology and health, which is specifically targeted at building practitioner understanding to develop improved soil management and which will be tested at knowledge exchange events particularly within WP3 Project 10. This will lead to a greater awareness amongst growers of (a) the impacts of soil management and crop selection, and (b) the complexity of biological interactions in soil.

To update the scientific knowledge on soil biology and soil health we undertook a literature review of articles published since 2008 (date of a recent significant review) that were accessible through the Web of Science database or in reports and other 'grey' literature known to the team. We tabulated the effects of the different management options identified on the biological, physical and chemical properties of soil. Some of the management options were specific and well acknowledged i.e. reduced tillage, added organic matter, residue retention, fertiliser addition, liming, strip tillage, controlled drainage, controlled traffic, biocides, buffer strips, plastic mulch and adding earthworms, however, others were more general and less specific such as conservation agriculture (including cover crops), plant diversity and organic farming. There are still gaps in the knowledge for the less common management options especially for interactions between soil type and climate as well as for combinations of management options. To generate the visual tool the effects of the management options were modified semi-quantitatively according to soil type (light, medium or heavy), UK climatic zone (cool & dry; cool & wet; warm & dry; warm & wet) and generic agricultural practices (combinable arable; arable & root crops; grass). A visual tool was developed which presented the likely magnitude of the effects of representative management options (reduced tillage; no-tillage; cover crops; carbon-rich or nitrogen-rich organic amendments) on a suite of biological, physical, chemical and economic outputs. The model and the rationale behind the model were presented at a technical workshop and two industry workshops. Feedback from those workshops will be carried forward to Work Package 3, where it will be used to update the model and the visual tool to maximise awareness amongst growers.

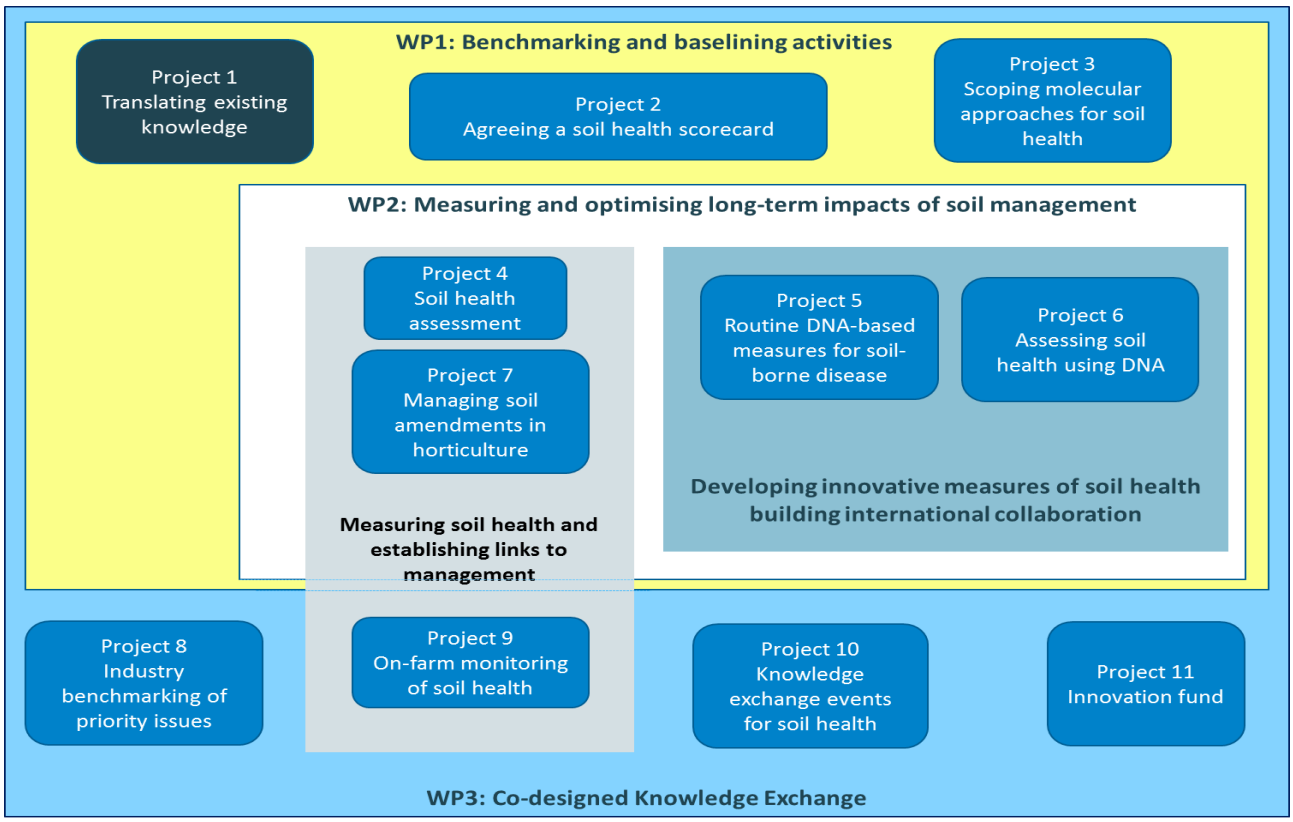

Figure 1. Diagram to show how project 1 (in black) fits into the organisation of the Soil Biology and Soil Health Partnership.

2. Literature search to update the existing scientific reviews of soil biology and soil health

2.1. Methodology

The project team had led two previous extensive reviews in this area published as Stockdale and Watson (2009; 2012). Therefore in this project, an initial search of literature, using the Web of Knowledge databases from 2008 (that would have covered publications up to 2008 at least) to the present (end 2016), was done using the following specific search terms:

SOIL AND HEALTH AND ! or SOIL AND QUALITY AND !, or SOIL BIOLOGY AND ! where ! was one of the main management options of soil health/quality identified in the proposal.

Namely *TILLAGE, SOIL ORGANIC MATTER, DRAINAGE, pH, ROTATION, CROP*, each used individually.

A search using SOIL QUALITY OR SOIL HEALTH gave 44,439 records in total within the Web of Knowledge databases (2008-2016).

Using the search terms specified (!) these were narrowed down to 29,970 individual papers. This was further reduced to 1,962 by initially focussing on review papers. After screening for relevance from the article title and abstract (i.e. the review would have to be either relevant to UK type climatic conditions and agricultural practices, or present generally applicable principles relating to soil biology and soil quality) a total of 88 review papers were evaluated.

These reviews were found in the following publications:

- Advances in Agronomy (4)
- Agricultural Systems (1)
- Agriculture, Ecosystems and Environment (1)
- Agronomy for Sustainable Development (13)
- Annual Review of Phytopathology (1)
- Applied Ecology and Environmental Research (1)
- Applied Soil Ecology (5)
- Archives of Agronomy and Soil Science (1)
- Biology and Fertility of Soils (2)
- Biotechnologie Agronomie Societie et Environment (2)
- British Food Journal (1)
- California Agriculture (1)
- Critical reviews in Plant Science (1)
- Current Opinion in Environmental Sustainability (2)
- Current Science (1)

- Ecological Indicators (2)
- Environmental Chemistry Letters (1)
- Experimental Agriculture (1)
- Frontiers in Plant Science (1)
- Geoderma (1)
- Global Change Biology (3)
- ISME Journal (1)
- Journal of Chemical Ecology (1)
- Journal of Soil Science and Plant Nutrition (1)
- Journal of the Science of Food and Agriculture (1)
- Land Use Policy (1)
- New Zealand Journal of Agricultural Research (1)
- Open Geosciences (1)
- Phyton (1)
- Plant and Soil (1)
- Renewable Agriculture and Food Systems (1)
- Revista Brasileira de Ciencia do Solo (1)
- Science of the Total Environment (2)
- Scienta Agricola (1)
- Soil and Tillage Research (3)
- Soil Biology & Biochemistry (7)
- Soil Change Matters (IOP conference series) (1)
- Soil Research (3)
- Soil Science Society of America Journal (2)
- Soil Use and Management (3)
- Sustainability (2)
- Water, Air and Soil Pollution (1)

(A full list of these references according to subject area is given in Appendix 1)

In addition to the systematic Web of Knowledge search a further 19 reports, in the so-called 'grey' literature, specifically known by the participants to be relevant were evaluated. These included:

- Environment Agency Science Report SC 030265 The development and use of soil quality indicators for assessing the role of soil in environmental interactions. Merrington, G. *et al*. 2006.
- DEFRA report - Indicators of soil quality – physical properties (SP1611). Rickson .R.J. *et al*. 2013.

- Soil Security Programme - How do we define and measure soil health, Post Workshop Report. 2016.
- JNCC Report No: 364 Do farm management practices alter below-ground biodiversity and ecosystem function? Implications for sustainable land management. Stockdale, E.A. *et al*. 2006.
- Environment Agency Science Report SC 050054SR2 Road Testing of 'Trigger Values' for assessing Site Specific Soil Quality. Phase 2 – Other Soil Quality Indicators. Bhogal, A. et a. 2008.
- Defra Project No. SP0529 SQID: Prioritising biological indicators of soil quality for deployment in a national-scale soil monitoring scheme Summary report. Black, H.I.J. *et al*. 2008.
- Defra Soils Research – Evidence Review Final Report. Smith , K. *et al*. 2015
- AHDB Research Review No. 90 A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species. White, C.A. *et al*. 2016
- HGCA Research Review No. 81 Straw incorporation review. Nicholson, F., 2014
- SmartSoil Deliverable D3.4: Modelling constraints and trade-offs in optimizing SOC. Glenk, K. *et al*. 2015.
- Defra BD5001: Characterisation of Soil Structural Degradation Under Grassland and Development of Measures to Ameliorate its Impact on Biodiversity and Other Soil Functions. Newell-Price, P. *et al*. 2012.
- SAC technical notes (https://www.sruc.ac.uk/downloads/120202/technical_notes).

Thus, a total of 107 reviews, papers and reports were used to update the comprehensive knowledge already available and summarised in Stockdale and Watson (2012). Managing soil biota to deliver ecosystem services, Natural England Commissioned Report NECR100.

2.2. Key findings

Advances in understanding the factors contributing to soil health since the previous review of Stockdale and Watson (2012), have largely been to add detail in two main subject areas. Firstly on the effects that different management strategies have on soil health parameters and, secondly, on the beneficial effects that soil health parameters have on agricultural outcomes. Thus, in the case of earthworms which are a key biological indicator of soil health (see for example Project 2), there have been meta-analyses looking at the effects of tillage on earthworms and also on the beneficial effects of earthworms on crop yield. The effects of tillage (van Capelle *et al*., 2012) can now be broken down according to soil type (sand, silt, clay, loam), extent of tillage (conventional plough, minimum tillage, no tillage) and by the different ecological groups of earthworms. This means that the effects of the selected management options (tillage, soil organic matter, drainage, pH, rotation, crop) on

earthworms can be modified according to environmental conditions. The practical contribution of the key indicators of soil health to agronomic output has also been quantified in greater detail. Again in the case of earthworms, another meta-analysis (van Groenigen *et al*., 2014) has quantified the increase in crop yield due to the earthworm effect for different crop types and environmental conditions. This provides a much stronger evidence for including many of the indicators as there are now quantifiable beneficial effects. Similar benefits have also been shown for the general nematode community (Gebremikael *et al*., 2016), which includes bacterial-feeders, fungal-feeders, omnivores and predators and not simply the plant-parasites that are the focus of many soil tests. A meta-analysis of cover crops has shown that effects on yield depended on: the crop type (maize or soyabean), the cover crop (legume or non-legume) and soil type (light or heavy) (Alvarez *et al*., 2017). The practice of no-till has similarly been shown to positively affect crop yield and soil properties, depending on the background soil conditions, crop type and fertiliser regime (Zhao *et al*., 2017). Reports on the effects of other tillage practices are also emerging, such as the positive effect of strip tillage on soil properties and yield (Leskovar *et al*., 2016). The bibliography related to these effects is given in Appendix 1 and the broad direction of the effects of the management options on soil biological, physical and chemical soil attributes identified from the literature search are indicated in Table 1 (see later). This information forms the basis of the semi-quantitative model described in section 3.

The most important consequences for understanding what soil health is and how best to communicate that knowledge can be distilled from a series of reviews related to the monitoring of soil health, and the effects of management options such as straw incorporation and cover crops (Black *et al*., 2008; Nicolson *et al*., 2014; Rickson *et al*., 2013; Smith *et al*., 2015; White *et al*., 2016; Stockdale and Watson, 2012).

The main general points arising from these integrated reviews are:

- *"Soil health is the capacity of soil to function as a living system, within ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production*" (FAO, 2008).
- Assessment of soil health requires a consideration of chemical, physical and biological characteristics of soil; these are often strongly interdependent and hence there is no single recommended approach for the characterisation and measurement of soil health. The complexity of the interactions with biological functions can probably be best explained in the linked diagrams, Figures 2 and 3. These show the complexities of the microbial soil food web

and then how that food web forms part of a hierarchy of biological, physical and chemical interactions leading to soil health.

- Site/environmental factors control some soil properties such as texture, depth, and hydrological functions (receiving / shedding site etc) and these unmanageable factors set site-specific constraints to the size, diversity and activity of soil biology and also soil function. They will also affect the capability of the farmer/ grower to adopt changed practices.
- The main management options relating to soil health are: tillage; soil organic matter; drainage; liming to increase soil pH; crop; and rotation.

General principles for soil management can be drawn out of the literature (Figure 4) but their implementation requires the development of locally-adapted practices which fit the soil type / climate and agricultural system

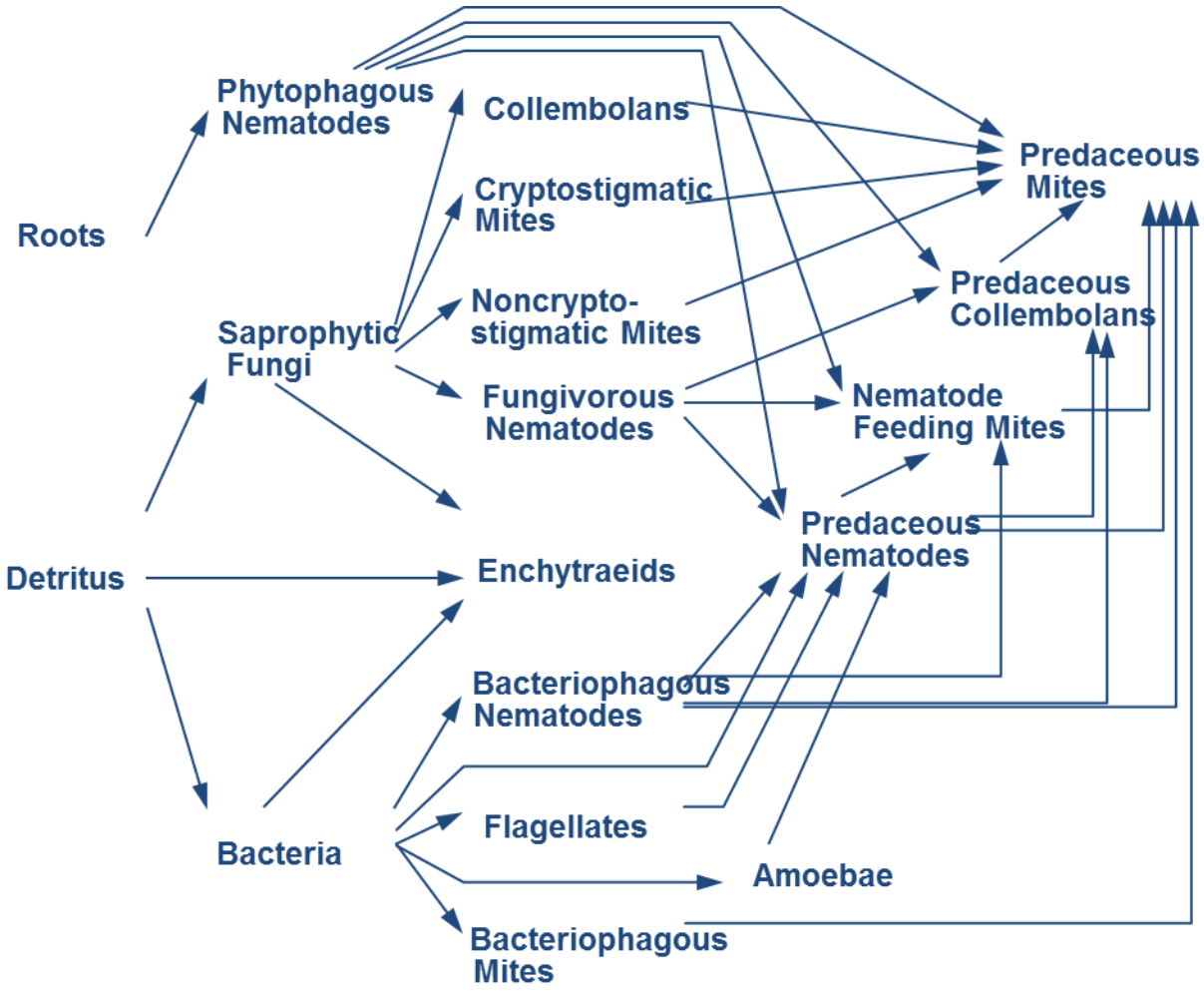

Figure 2: A diagram representing the soil food web, showing the flows of energy (i.e. carbon, and therefore nitrogen and other nutrients) through the main trophic groups of microorganisms, micro- and mesofauna in a typical UK agricultural soil (de Ruiter *et al*., 1993).

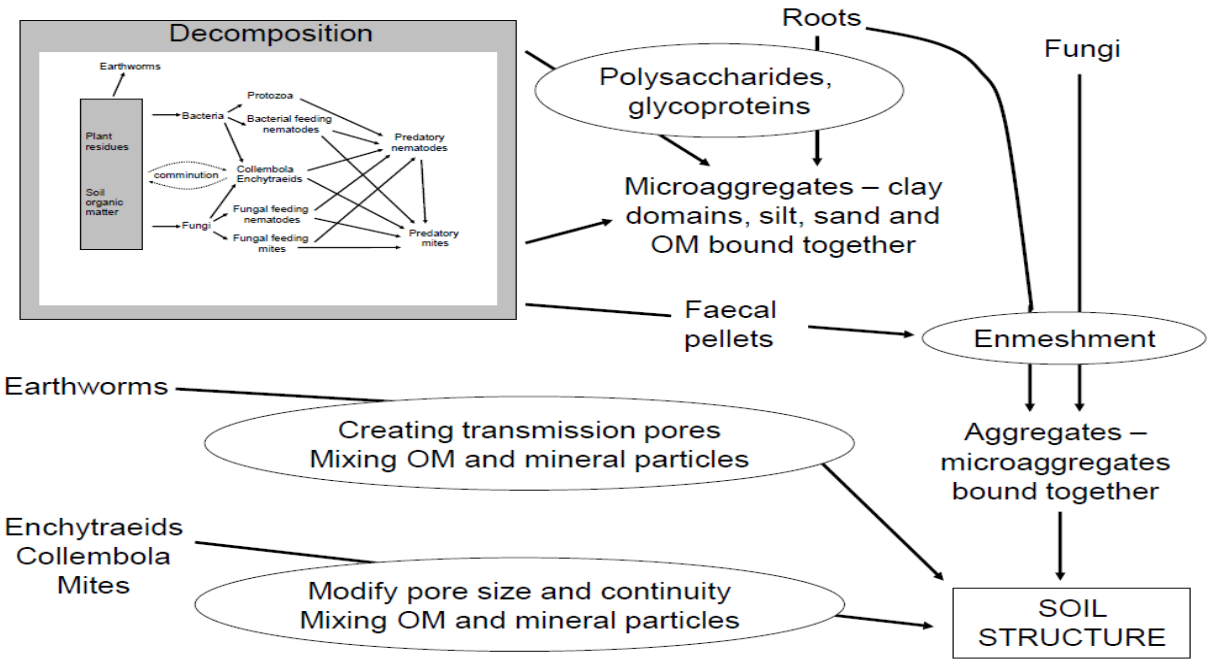

Figure 3: Diagram to show how the soil food web, within the decomposition box, interacts with other biological, chemical and physical factors in the soil to create soil structure. Stockdale and Watson, 2012.

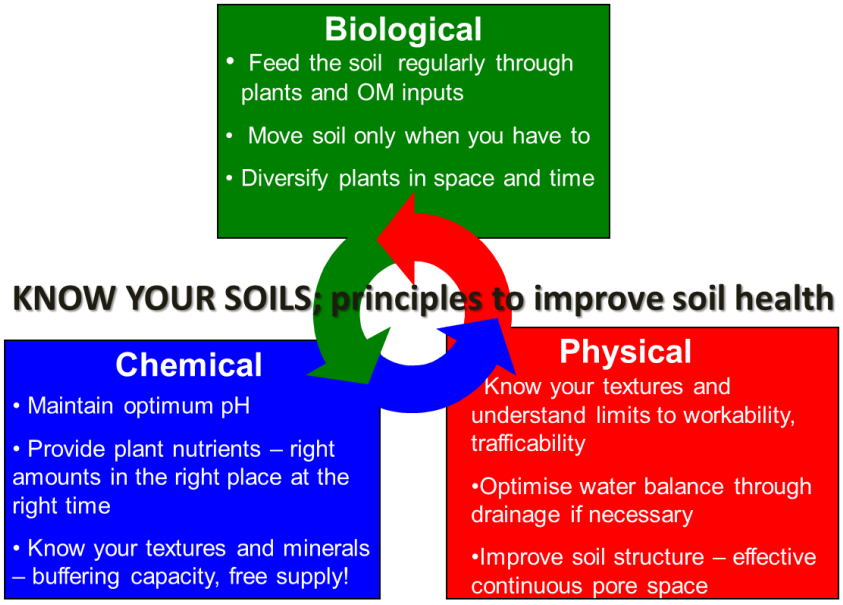

Figure 4. A summary of the key principles underpinning the development of farm management practices to improve soil health.

Detailed background to these conclusions is available online (http://publications.naturalengland.org.uk/publication/2748107); the report is freely available for use and re-use under the Open Gov licence subject to certain conditions (see Copyright).
Knowledge gaps still exist in our understanding of soil health, in particular:

- Rickson *et al* (2013), who just covered physical measures of soil quality, considered that although narrative links could be described between soil properties and soil functions, there was insufficient knowledge even to construct a conceptual model for the interactions between physical measures of soil quality, soil processes and functions.
- There is lack of quantitative information on the impacts of cover crops to guide decision-making; priority areas for more research are effects on pests and diseases, effects on N (particularly for amending subsequent fertilisation regimes) and effects on SOM (White *et al*. 2016).
- There is a paucity of information of the effects of soil management practices on ecosystem services beyond food/fibre production i.e. nutrient cycling, water retention, biodiversity and habitat and storing, filtering and transforming compounds, as detailed by Smith *et al*. (2015).

However, the literature reviewed was useful in adding more specific detail to our knowledge of the effects of individual driving factors on different components of soil quality (Table 1 and Appendices 1 and 4). Tabulating the effects of the main management options (change in agricultural practice) against measures of soil quality (Table 1) shows that comprehensive information is only available for some of the management options (reduced tillage, added organic matter, plant biodiversity, conservation agriculture and crop residue management). Even here it is often only for specific crop/soil/climate combinations or expressed in terms of general principles. The remaining management options are sparsely populated in the table and this reflects more specific concerns related to these practices (e.g. effects of plastic mulch on earthworms).

Table 1. Summary of the literature review to show effects of agricultural management options (reduced tillage, organic matter addition, etc) on soil biological, chemical, or physical effects and crop yield. Effects are either positive (+) or negative (-) compared to a conventional management option, or there is no information (blank). References generating this information are listed by subject area in Appendix 1, with hyperlinks to the online versions of the papers in Appendix 4 .

	Biology								**Chemistry**					**Physics**		**Yield**
	Earth worms	Microbial biomass	Enzyme Activities	Bio-diversity	Natural enemies	Fewer Slugs	Fewer Weeds	Less Disease	Soil organic matter	Less Nutrient loss	Less Herbicide use	Less Pesticide loss	Nutrient Availability	Soil structure	Traffic-ability	Yield
Reduced tillage	+	+	+	+	+	-	-	-	+	+	-			+/-	+	-
Organic matter addition	+	+	+					-	+			+	-	+		+
Conservation agriculture	+	+	+	+		-			+					+		-
Grass ley	+	+	+	+			+	+	+					+		
Crop residue addition	+	+	+					-	+	+				+		+/-
Organic vs conventional		+	+	+					+	+				+		-
Fertiliser input		+	+						+	-				+		+
Controlled drainage										+					-	-
Liming	+													+		+
Strip tillage		+														-
Controlled traffic														+		+
Biocides	-		+/-													
Buffer strips										+		+				
Plastic mulch	-															
Earthworm addition																+

3. Development of a descriptive (semi-quantitative) model

The effects of the agricultural management options (management variables) are modified by agronomic conditions across the UK. Expert knowledge drawing from an understanding of the underlying principles of soil/plant/organism/environment interactions was needed to interpolate and extend the results of the literature review, to give a full coverage for UK agricultural systems and to consider how any general findings might be adjusted as a result of soil/ region specific nuances. Thus, the table (Table 1) was expanded to include mycorrhizal fungi, soil biota, the extra soil chemical parameters of pH, N, P, K and cation exchange capacity and the physical parameter of water infiltration. The effects of the management options (i.e. positive or negative in Table 1) was further modified by regional climate, soil type and farming system prevalent in the UK.

The expert opinion of the project partners was used to apply the modifications and thus Table 2 shows how the effect of each driver is moderated or exaggerated by:

- soil type (simplified to light (sandy), medium or heavy (clay-rich),
- regional climate (simplified to cold & wet; cold & dry; warm & wet; warm & dry)
- main agricultural systems (combinable arable, arable including root crops, grass)

As an example from Table 2, effects of management options on earthworms are likely to be more pronounced in heavy soils (+1) and less pronounced in light soils (-1). A combination of the effect (Table 1) and the modification (Table 2) then gives a semi-quantitative outcome for the scenarios (Table 3). Here we have applied the general finding that the effects of reduced tillage are c. 75% of that for no-tillage (Peigné *et al*., 2007).

This leads to a set of tables (Appendices 2 and 3) equivalent to the example given in Table 3. In Appendix 2 the tables show how the management options are give a numerical value and combined with the moderating effects of the farm attributes. Appendix 3 then shows how the effects of representative management options are estimated for each of the farm attribute combinations.

Although we have simplified some of the management options here (e.g. addition of organic matter) it is clear that some of the management options will also require further sub-division, as the effects of stabilised compost are shown in some circumstances to differ from cattle slurry or an anaerobic digestate (RB209). Another practical consideration that is missing from the research available to the literature review is that farmers and growers are likely to implement a range of management options simultaneously (such as reducing tillage and growing a cover crop) so a range of interacting scenarios will need to be considered as the model and prototype visual tool is further developed in WP3. However, the results of the literature review provide the scientific understanding of the mechanisms behind the changes in soil quality (e.g. reducing tillage reduces soil mixing so that organic matter and minerals concentrate in the upper topsoil increasing labile carbon content, nutrient turnover and microbial activity). These mechanisms are explained in more detail in Soane et al., (2012) and Stockdale and Watson (2012) available at
http://publications.naturalengland.org.uk/publication/2748107

Table 2. Summary of how farm attributes (soil type, regional climate, agricultural system) will moderate the magnitude effects of the management options detailed in Table 1 on soil parameters. The biological, chemical and physical parameters have been expanded to include mycorrhizal fungi (AMF),soil biota, soil nitrogen (N), phosphorus (P), potassium (K), pH, cation exchange capacity (CEC) and water infiltration. The direction of the driver effect (positive or negative from Table 1) is not changed but the magnitude of that effect is weaker (-1) or stronger (+1) depending on the farm attributes.

		Farm attributes									
		Soil type			**Regional climate**				**Agricultural system**		
		sand	**medium**	**clay**	**cold/wet**	**cold/dry**	**warm/wet**	**warm/dry**	**arable-combinable**	**arable-roots**	**grass**
Biology	earthworms	-1	0	1	0	-1	1	-1	0	-1	1
	microbial biomass	-1	0	1	0	-1	1	-1	0	0	1
	enzyme activity	1	1	0	0	0	1	1	0	0	1
	natural enemies	0	0	0	0	-1	1	-1	0	-1	1
	AMF	0	0	0	0	-1	1	-1	0	-1	1
	soil biota	0	1	0	0	-1	1	-1	0	-1	1
	slugs	-1	-1	0	0	-1	1	0	0	0	0
	weeds	-1	-1	-1	-1	-1	-1	-1	0	0	-1
	disease	-1	-1	-1	-1	-1	1	1	0	0	0
Chemistry	SOM	-1	-1	-1	-1	-1	1	1	-1	-1	-1
	N	-1	0	1	1	1	1	-1	-1	-1	1
	P	-1	0	1	1	0	0	-1	-1	-1	0
	K	-1	0	0	0	0	0	0	0	0	0
	pH	-1	0	1	0	0	0	0	0	0	0
	CEC	-1	0	0	0	0	0	0	0	0	0
	Nutrient loss	-1	0	1	0	0	0	0	0	0	0
	Herbicide	0	-1	0	0	-1	1	-1	0	1	-1
	Pesticide loss	0	0	0	0	0	0	0	0	0	-1
	N loss	-1	0	1	0	0	0	0	0	0	0
	soil structure	1	0	-1	-1	0	-1	1	0	0	1
Physics	water infiltration	1	0	0	0	0	0	0	0	0	1
	trafficability	-1	1	1	0	0	0	0	0	0	1
Yield	Yield	-1	0	1	0	-1	1	0	0	0	0

Table 3. An example of the semi-quantitative outcomes of the modified effects of agricultural management options on soil health parameters, compared to a conventional management option. This example is for the scenario of an arable including root crops system, in a warm & wet climatic zone on a light (sandy) soil. The changes are strongly positive or strongly negative (++, - -), positive or negative (+, -) or neutral (=)

	Management option					
	Reduced tillage	High C Organic Matter	High N Organic Matter	Cover crops	Reduced tillage, high C OM, cover crops	Reduced tillage, high N OM, cover crops
earthworms	++	+	0	+	++	++
microbial biomass	+	++	+	++	++	++
enzyme activity	+	+	0	+	+	+
natural enemies	+	+	+	+	++	++
AMF	+	0	0	+	++	++
soil biota	+	+	+	+	++	++
Fewer slugs	-	0	0	0	-	-
Fewer weeds	-	0	0	-	=	=
Less disease	-	0	0	0	=	=
SOM	+	+	+	+	-	-
N	0	0	0	+	+	+
P	0	0	+	0	=	=
K	0	+	0	0	+	+
pH	0	0	0	0	++	+
CEC	0	+	0	0	+	+
Less nutrient loss	+	-	-	+	=	-
Less herbicide	-	0	0	0	-	=
Less pesticide loss	0	0	0	0	=	=
Nutrient availability	0	-	-	0	-	=
soil structure	+	0	0	0	+	+
water infiltration	-	+	0	0	+	+
trafficability	+	+	0	0	+	+
Yield	-	+	+	0	=	=

4. Communicating the information to farmers / growers using a visual tool

Given the complexities in the interactions between management practices and the physical, chemical and biological properties of soil, their interaction and consequent soil function, simple predictions of impacts are not possible. In fact, farmers themselves routinely mention that the same management practice can result in different effects in different seasons or on different soil types. In addition, Sherwood and Uphoff (2000) note that one of the challenges for improving soil management is that of supporting farmer engagement with information so that they can identify and prioritise problems and opportunities, test and evaluate innovations and become partners in sharing the information gained. Hence as well as providing materials to describe the underpinning principles and case-studies to highlight the site-specific impacts of particular practices, the project has sought to develop a visual tool which allows farmers to investigate the impacts of a range of management scenarios and thereby to make the descriptive model an effective tool for knowledge exchange.

The tool is designed to display the likely effects of the different management scenarios visually, in a way that shows both the complexities (i.e. the interconnections between physics, biology and chemistry) and the trade-offs (e.g. that with added compost you are likely to increase the positive biological attributes and yield, even though you may immobilise nutrients and need more effective weed control). The tool as described here is a prototype version that will be further developed throughout the project, in light of the practical results from WP 2 and as a result of the KE activities in WP 3. Essentially the prototype tool converts the scenario outcomes from Table 3 into a single table for each scenario (that is each combination of soil type, climatic zone, and agricultural system) and gives the outcomes for each of the soil parameters in a graded traffic light system. So, green for positive outcomes for the grower and the environment and red for negative outcomes. The more intense the colour the stronger the effect. The user selects values for their climate, soil and agricultural system from drop down menus and then selects the practice about which they want to know more, this then presents the scenario outcomes on screen. In the prototype tool the farmer would be offered a choice of field conditions to most closely match their situation and a choice of management options to choose from (see example in figure 5), the likely effects on soil health are then calculated and presented in the traffic light format but also with a summary of likely effects on farm margins, summary pro's and con's, and links to up to 4 key references (as in figure 6). Because of the patchy nature of the scientific evidence for the effects of management options on all aspects of soil biology (see Table 1), we have combined the responses of earthworms, microbial biomass, soil enzymes, mycorrhizal fungi (AMF), natural enemies and soil biota into a single category – positive biology.

Management Effects on Soil Health		
Field Conditions		
Please enter the conditions for your field		
Soil Type i.e. Sandy, Medium or Clay	Sandy	
Climate i.e. Cold Wet, Cold Dry, Warm Wet or Warm Dry	Cold Wet	
Cropping i.e. Arable-combinable, Arable-roots or Grass	Arable-combinable	
Management Change		
Please enter **Management Change**	No Tillage	
This can be:		
No Tillage		
Reduced Tillage		
High C Organic Matter		
High N Organic Matter		
Cover Crop		

Figure 5: Screenshot to show the options available to the user of the prototype visual tool, giving choices of relevant soil type, climate and cropping system on which to explore the likely effects of a range of management changes.

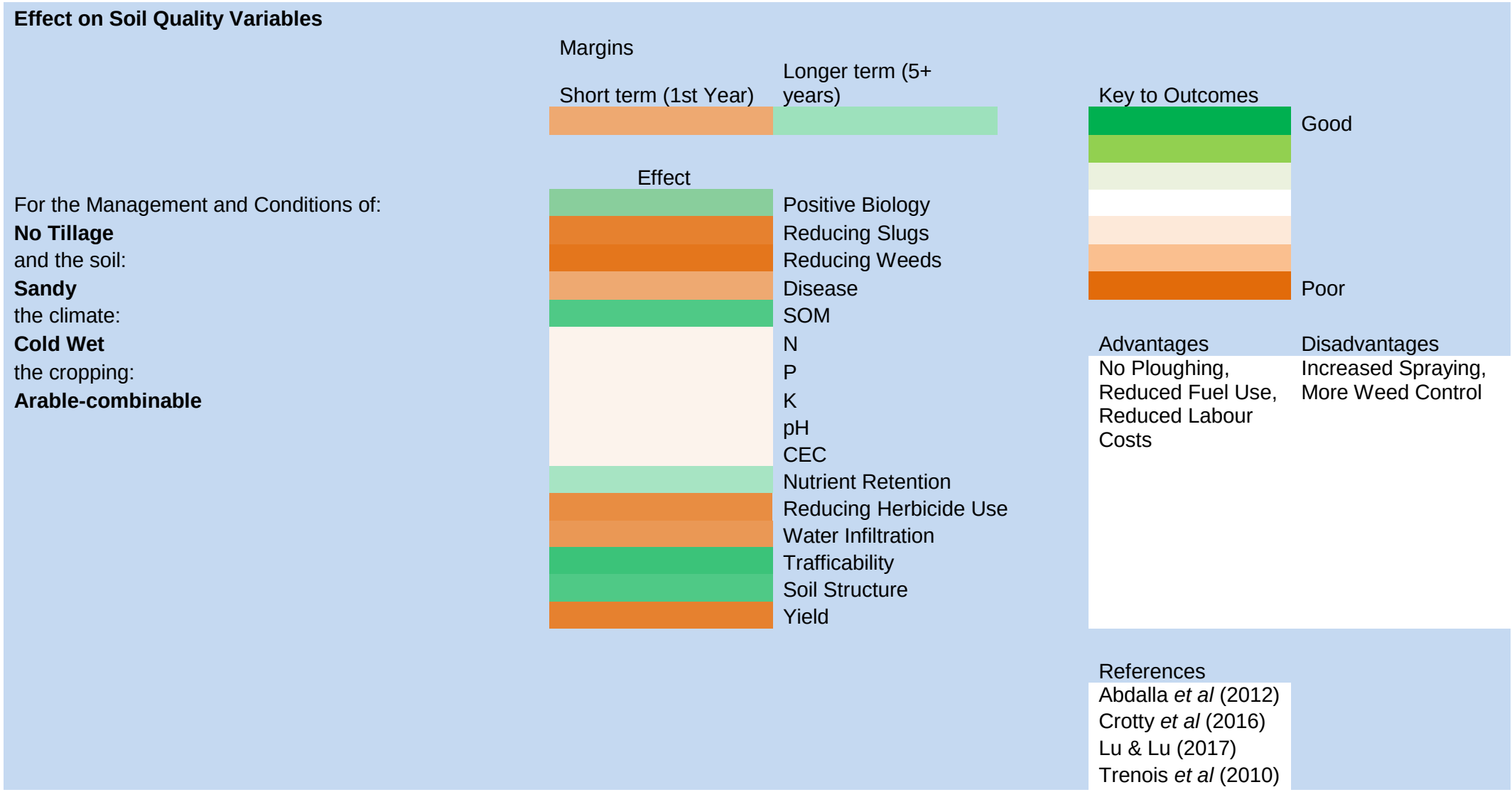

Figure 6. Screenshot of the outcome of the visual tool showing the effects of implementing no-tillage on a sandy soil in a cold & wet climatic zone for a combinable arable system. Several aspects of this screenshot show that this is a prototype version and continued development in workpackages 2 and 3 will be required. The positive biology category encompasses effects on earthworms, microbial biomass, soil enzymes, mycorrhizal fungi (AMF), natural enemies and soil biota. The prototype visual tool will be 'sense-checked' as part of projects 8 and 9.

In the initial phase, the project team tried to strike a balance which did not i) make either the input required or the output presented too complex and ii) make the output too simple or general – where either of these outcomes result then the approach is more likely to be off-putting than engaging. Taking the practical point of view that the tool should help support decision-making, the project partners considered that:

- positive biological attributes could be reported together as there are no management decisions dependent on which aspect of the positive biology is affected
- water infiltration and soil structure can also be reported together as they are interdependent
- detailed information on the negative attributes would be of use when thinking about management options
- individual nutrients and pH are already part of the soil reporting commonly used so that growers would be used to that information

5. Conclusions

It is clear in conversations with farmers, policy-makers and in the context of multi-disciplinary research groups that providing an integrating description and measure of soil health has immense conceptual appeal, but when we move towards practical development within the soil science/ agronomy community, it is also clear that it is very difficult to implement operationally. All studies of soil function (as summarised clearly by Wardle and Giller, 1996; Young and Ritz, 1998) show that soil processes result from the interaction of soil organisms, their resources (e.g. organic materials) and habitat (e.g. soil pore size distribution). However, the array of possible spatial configurations is too great, the range of relevant scales too broad and the diversity of responses to the patterns in space and time too large to allow easy modelling. Consequently at the scale of farming systems, the scientists' understanding of impacts of management on soil health is incomplete and, where it does exist, fairly sketchy. But there is increasing evidence that increased OM inputs (diversity) and reduced tillage act together to promote increased biological activity. There is some indication that resilience to extreme events may be increased as a result (Stockdale and Watson 2012). More recent studies are now showing statistically significant correlations between increases in soil health and increased crop yield (Liu *et al* 2017, Zhao *et al*., 2017), cover crops and crop yield (Alvarez *et al*., 2017)

Improvement in soil management also requires improved communication of the impacts of crop and soil management measures in combination on soil function and health. Griffiths *et al.* (2015) showed that the relative importance of site, soil and management options varies in each location and consequently noted that site-specific guidance is needed to maintain soil health. Although there is much more still to discover and new experiments needed to fully elucidate the relationships between soil biology, soil health and crop health/ productivity, there is nonetheless detailed knowledge

available on the effects of management options on soil biology and health for the main soil/ climate/ crop scenarios relevant to the UK. Expert knowledge is also able to take the general principles emerging from research and apply them to un-studied scenarios to predict the likely impacts; this can be captured to inform knowledge exchange through descriptive modelling.

A summary of background information about soil health and together with some of the more detailed findings of the literature review were presented to a technical workshop (for researchers and agronomists held in Cambridge in October 2017) and two industry workshops (for farmers, growers, agronomists held in Northumberland and Gloucestershire in November 2017). Over 60% of the attendees at the consultation workshops were not fully satisfied with the information they currently access on soils and their management and all felt that the materials arising from the literature review (i.e. Table 1) provided a good basis for the development of introductory materials on soil health for farmers and growers. As part of Project 10, the Programme will therefore draw from feedback on the most appropriate KE mechanisms to develop a suite of KE outputs from the information brought together in the literature review.

The workshops also reviewed the early version of the visual tool. Feedback provided support for the general approach and gave many suggestions on ways to improve the utility of the visual tool. This detailed feedback is reported separately (Project 8) and the further development of the underpinning descriptive model and associated visual tool will continue through the rest of the programme. The descriptive model will be evaluated and further updated as needed using the results of the assessments made in WP2 and Project 9 and farmer feedback will be used to refine the visual tool as part of work in Project 10. There will also be on-going ‘sense checking’ of the visual tool throughout the lifetime of the partnership.

6. References

Alvarez, R., Steinbach, H.S., de Paepe, J.L. (2017). Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis. *Soil & Tillage Research*, 170: 53–65.

Bhogal, A., Boucard, T., Chambers, B. J., Nicholson, F. A., Parkinson, R. (2008). Road Testing of 'Trigger Values' for Assessing Site Specific Soil Quality. Phase 2 – Other Soil Quality Indicators. Environment Agency, Science Report – SC050054SR2.

Black, H.I.J., Ritz, K., Campbell, C.D., Harris, J.A, Wood, C., Chamberlain, P.M., Parekh, N., Towers, W., A. Scott, A.(2008). SQID: Prioritising biological indicators of soil quality for deployment in a national-scale soil monitoring scheme. Summary report Defra Project No. SP0529.

De Ruiter, P.C., Moore, J.C., Bloem, J., Zwart, K.B., Bouwman, L.A., Hassink, J., de Vos, J.A., Marinissen, J.C.Y., Didden, W.a.M., Lebbink, G., Brussaard, L. (1993). Simulation of nitrogen dynamics in the blowground food webs of two winter-wheat fields. *Journal of Applied Ecology*, 30:95-106.

FAO. (2008). An international technical workshop: Investing in sustainable crop intensification The case for improving soil health. *Integrated Crop Management* Vol.6. FAO, Rome: 22-24 July 2008.
Glenk, K., Shrestha, S. (2015). Deliverable D3.4: Modeling constraints and trade-offs in optimizing SOC. SmartSoil.

Gebremikael, M.T., Steel, H., Buchan, D., Bert, W., de Neve, S. (2016). Nematodes enhance plant growth and nutrient uptake under C and N-rich conditions. *Scientific Reports*, 6:32862. DOI: 10.1038/srep32862.

Glenk, K., Shrestha, S., Topp, C.F.E., Sanchez, B., Iglesias, A., Dibari, C., Merante, P. (2015). Deliverable D3.4: Modeling constraints and trade-offs in optimizing SOC. Collaborative project KBBE-2001-5. Sustainable management of agricultural soils in Europew for enhancing food and feed production and contributing to climtae change mitigation (*Smart*Soil).

Griffiths, B.S., Hallett, P.D., Daniell, T.J., Hawes, C., Squire, G.S., Mitchell, S.M., Caul, S., Valentine, T.A., Binnie, K., Adeloye, A.J., Rustum, R., Nevison, I. (2015). Probing soil physical and biological resilience data from a broad sampling of arable farms in Scotland. *Soil Use and Management*, 31: 491–503.

Leskovar, D., Othman, Y., Dong, X. (2016). Strip tillage improves soil biological activity, fruit yield and sugar content of triploid watermelon. *Soil & Tillage Research*, 163:266–273.

Liu, J., Wu, L., Chen, D., Li, M., Wei, C. (2017). Soil quality assessment of different *Camellia oleifera* stands in mid-subtropical China. *Applied Soil Ecology*, 113: 29–35.

Merrington, G., Fishwick, S., Barraclough, D., Morris, J., Preedy, N., Boucard, T., Reeve, M., Smith, P., Fang, C. (2006). The development and use of soil quality indicators for assessing the role of soil in environmental interactions. Environment Agency, Science Report SC030265.

Newell-Price, P., Chambers, B., Whittingham, M. (2012). Characterisation of soil structural degradation under grassland and development of measures to ameliorate its Impact on biodiversity and other soil functions. DEFRA report BD5001.

Nicholson, F., Kindred, D., Bhogal, A., Roques, S., Kerley, J., Twining, S., Brassington, T, Gladders, P., Balshaw, H., Cook, S., Ellis, S. (2014). HGCA Research Review No. 81 Straw incorporation review.

Peigné, J., Ball, B.C., Roger-Estrade, J., David, C. (2007) Is conservation tillage suitable for organic farming? *Soil Use and Management,* 23: 129-144.

RB209 AHDB nutrient management guide. https://ahdb.org.uk/projects/RB209.aspx

Rickson, R.J., Deeks, L.K., Corstanje, R., Newell-Price, P., Kibblewhite, M.G., Chambers, B., Bellamy, P., Holman, I., James, I.T., Jones, R., Kechavarsi, C., Mouazen, A.M., Ritz, K., Waine, T. (2013). Indicators of soil quality – physical properties. DEFRA report SP1611.

Sherwood, S., Uphoff, N. (2000). Soil health: research, practice and policy for a more regenerative agriculture. *Applied Soil Ecology,* 15: 85-97.

Smith K., Newell-Price, P., Bhogal, A., Sagoo, L., Collins, C. (2015). Defra Soils Research – Evidence Review Final Report.

Soane, B.D., Ball, B.C., Arvidson, J., Basch, B. Moreno, F., Roger-Estrade, J. (2012). No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil & Tillage Research*, 118: 66-87.

Soil Security Programme (2016). How do we measure and defeine soil health? Post workshop report.

Stockdale, E.A., Watson, C.A., Black, H.I.J., Philipps, L. (2006). JNCC Report No: 364 Do farm management practices alter below-ground biodiversity and ecosystem function? Implications for sustainable land management.

Stockdale, E.A., Watson, C.A., 2009 Biological indicators of osil quality in organic farming systems. *Renewable Agriculture and Food Systems*, 24: 308–318.

Stockdale, E.A., Watson, C.A., 2012 Managing soil biota to deliver ecosystem services. Natural England Commissioned Report NECR100

van Capelle, C., Schrader, S., Brunitte, J. (2012). Tillage-induced changes in the functional diversity of soil biota: A review with a focus on German data. *European Journal of Soil Biology,* 50: 165-181.

van Groenigen, J.W., Lubbers, I.M., Vos, H.M.J., Brown, G.G., de Deyn, G.B., van Grienigen, K.J. (2014). Earthworms increase plant production: a meta-analysis. *Scientific Reports*, 4 : 6365. DOI: 10.1038/srep06365.

Wardle, D.A., Giller, K.E. (1996). The quest for a contemporary ecological dimension to soil biology. *Soil Biology and Biochemistry,* 28: 1549-1554.

White, C.A., Holmes, H.F., Morris, N.L., Stobart, R.M. (2016). AHDB Research Review No. 90 A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species.

Young, I.M., Ritz, K. (1998). Can there be a contemporary ecological dimension to soil biology without a habitat? *Soil Biology and Biochemistry,* 30: 1229-1232.

Zhao, X., Liu, S-L., Pu, C., Zgang, X-Q., Xue, J-F., Ren, Y-X., Zhao, X-L., Chen, F., Lal, R., Zgang, H-L. (2017). Crop yields under no-till farming in China: A meta-analysis. *European Journal of Agronomy*, 84: 67–75.

7. Appendices

7.1. Appendix 1. Bibliography by subject area

Effects of tillage on soil health

Abdalla, M., Rueangritsarakul, K., Jones, M., Osborne, B., Helmy, M., Roth, B., Burke J., Nolan, P., Smith, P., Williams, M. (2012). How effective is reduced tillage–cover crop management in reducing N_2O fluxes from arable crop soils? *Water Air and Soil Pollution*, 223: 5155–5174.

Alva, A.K., Collins, H.P., Boydston, R.A. (2009). Nitrogen management for irrigated potato production under conventional and reduced tillage. *Soil Science Society of America Journal*, 73: 1496-1503.

Anderson, R.L. (2015). Integrating a complex rotation with no-till improves weed management in organic farming. A review. *Agronomy for Sustainable Development*, 35: 967–974.

Batlle-Aguilar, J., Brovelli, A., Porporato, A., Barry, D.A. (2011). Modelling soil carbon and nitrogen cycles during land use change. A review. *Agronomy for Sustainable Development*, 31: 251–274.

Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., Peigné, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegher, A. Döring, T.F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., Hammerl, V., Huiting, H., Leithold, G., Messmer, M., Schloter, M., Sukkel, W., van der Heijden, M.G.A., Willekens, K., Wittwer, R., Mäder, P. (2016). Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. *Agronomy for Sustainable Development*, 36: 22.

Crotty, F.V., Fychan, R., Sanderson, R., Rhymes, J.R., Bourdin, F., Scullion, J., Marley, C.L. (2016). Understanding the legacy effect of previous forage crop and tillage management on soil biology, after conversion to an arable crop rotation. *Soil Biology & Biochemistry*, 103: 241-252.

Dang, Y.P., Moody, P.W., Bell, M.J., Seymour, N.P., Dalal, R.C., Freebairn, D.M., Walker, S.R. (2015). Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: II. Implications for agronomy, soil and environment. *Soil & Tillage Research*, 152: 115–123.

Halvorson J.J., Liebig , M.A., Archer, D.W., West, M.S., Tanaka, D.L. (2016). Impacts of crop sequence and tillage management on soil carbon stocks in south-central North Dakota. *Soil Science Society of America Journal*, 80: 1003–1010.

Hebb, C., Schoderbek, D., Hernandez-Ramirez, G., Hewins, D., Carlyle, C. N., Bork, E. (2017). Soil physical quality varies among contrasting land uses in Northern Prairie regions. *Agriculture, Ecosystems and Environment*, 240: 14–23.

Horel, Á., Tóth, E., Gelybó, G., Kása, I., Bakacsi, Z., Farkas, C. (2015). Effects of land use and management on soil hydraulic properties. *Open Geosciences*, 1: 742–754.

Huang, M., Jiang, L., Zou, Y., Xu, S., Deng, G. (2013). Changes in soil microbial properties with no-tillage in Chinese cropping systems. *Biology and Fertility of Soils*, 49: 373–377.

Leskovar D., Othman, Y., Dong, X. (2016). Strip tillage improves soil biological activity, fruit yield and sugar content of triploid watermelon. *Soil & Tillage Research*, 163: 266–273

López Martínez, J.D., Vázquez-Vázquez, C., Salazar-Sosa, E., Zúñiga-Tarango, R., & Trejo-Escareño, H. I.*et al* (2010). Sistemas de labranza y fertilización en la producción de maíz forrajero. *Phyton*, 79: 47-54.

Lu, X. and Lu, X. (2017). Tillage and crop residue effects on the energy consumption, input–output costs and greenhouse gas emissions of maize crops. *Nutrient Cycling in Agroecosystems*, 08: 323–337.

Martínez, L. J.D., Vázquez, C. V., Sosa, E. S, Tarango, R. Z., Escareño, H.I.T. (2010). Tillage systems and fertilization on yield of forage maize. *International Journal of Experimental Botany*, 79: 47-54.

Nivelle, E., Verzeaux, J., Habbib, H., Kuzyakov, Y., Decocq ,G., Roger, D., Lacoux, J., Duclercq, J., Spicher, F.. Nava-Saucedo, J.-E, Catterou, M., Dubois, F., Tetua, T. (2016). Functional response of soil microbial communities to tillage, cover crops and nitrogen fertilization. *Applied Soil Ecology*, 108: 147–155.

Overstreet, L.F., and Hoyt, G.D. (2008). Effects of strip tillage and production inputs on soil biology across a spatial gradient. *Soil Science Society of America Journal*, 72: 1454-1463.

Roger-Estrade, J., Anger, C., Bertrand, M., Richard, G. (2010). Tillage and soil ecology: Partners for sustainable agriculture. *Soil & Tillage Research*, 111: 33–40.

Treonis, A.M. Austin, E.E., Buyer, J.S., Maul, J.E., Spicer, L., Zasada, I.A. (2010). Effects of organic amendment and tillage on soil microorganisms and microfauna. *Applied Soil Ecology*, 46: 103–110.

van Capelle ,C., Schrader, S., Brunotte, J. (2012). Tillage-induced changes in the functional diversity of soil biota e A review with a focus on German data. *European Journal of Soil Biology*, 50: 165-181.

Zhao, X., Liu, S-Li, Pu, C., Zhang, X-Q., Xue, J-F., Ren, Y-X., Zhao, X-L., Chen, F., Lal, R., Zhang, H-L. (2017). Crop yields under no-till farming in China: A meta-analysis. *European Journal of Agronomy*, 84: 67–75.

Zuber, S.M., and Villamil, M.B. (2016). Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. *Soil Biology & Biochemistry*, 97: 176-187.

Organic farming and organic amendments

Birkhofer, K., Smith, H.G., Rundlöf, M. (2016). Environmental impacts of organic farming. In: LS. John Wiley & Sons, Ltd: Chichester. DOI: 10.1002/9780470015902.a0026341

Cavigelli, M.A., Mirsky, S.B., Teasdale, J.R., Spargo, J.T., Doran, J. (2013). Organic grain cropping systems to enhance ecosystem services. *Renewable Agriculture and Food Systems*, 28(2): 145–159.

Diacono, M., and Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility. A review. Agronomy for Sustainable Development, 30: 401–422.

Henneron, L., Bernard, L., Hedde, M., Pelosi, C., Villenave, C., Chenu, C., Bertrand, M., Girardin, C., Blanchart, E. (2015). Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. *Agronomy for Sustainable Development*, 35: 169–181.

Lemtiri, A., Colinet, G., Alabi, T., Cluzeau, D. , Zirbes, L., Haubruge, É., Francis, F. (2014). Impacts of earthworms on soil components and dynamics. A review. *Biotechnology, Agronomy, Society and Environment*, 18(1): 121-133.

Lori, M., Symnaczik, S., MaÈder, P., De Deyn, G., Gattinger, A. (2017). Organic farming enhances soil microbial abundance and activity - A meta-analysis and meta-regression. *PLOS ONE*, https://doi.org/10.1371/journal.pone.0180442 July 12, 2017

Mondelaers, K., Aertsens, J., Van Huylenbroeck, G. (2009). A meta-analysis of the differences in environmental impacts between organic and conventional farming. *British Food Journal*, 111 (10): 1098-1119. doi.org/10.1108/00070700910992925

Murphy, B. (2015). Key soil functional properties affected by soil organic matter - evidence from published literature. IOP Conf. Series: *Earth and Environmental Science*, 25: 012008. doi:10.1088/1755-1315/25/1/012008

Reeve, J.R., Hoagland, L.A., Villalba, J.J., Carr, P.M., Atucha, A., Cambardella, C., Davis, D.R., Delate, K. (2016). Organic farming, soil health, and food quality: Considering possible links. In: Donald L Sparks (eds): *Advances in Agronomy,* 137: 319-368.

Rigby, H., Clarke, B.O., Pritchard, D.L., Meehan, B., Beshah, F., Smith, S., Porter, N. A. (2016). A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value for crop production and potential for emissions to the environment. *Science of the Total Environment*, 541: 1310–1338.

Sauvadet, M., Chauvat, M., Fanin, N., Coulibaly, S., Bertrand, I. (2016). Comparing the effects of litter quantity and quality on soil biota structure and functioning: Application to a cultivated soil in Northern France. *Applied Soil Ecology*, 107: 261–271.

Scotti, R., Bonanomi, G., Scelza, R., Zoina, A., Rao, M.A. (2015). Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. *Journal of Soil Science and Plant Nutrition*, 15(2): 333-352.

Stockdale, E.A. and Watson C.A. (2009). Biological indicators of soil quality in organic farming systems. *Renewable Agriculture and Food Systems*, 24(4): 308–318.

Tautges, N.E., Sullivan, T.S., Reardon, C.L., Burke, I.C. (2016). Soil microbial diversity and activity linked to crop yield and quality in a dryland organic wheat production system. *Applied Soil Ecology*, 108: 258–268.

Treonis, A.M. Austin, E.E., Buyer, J.S., Maul, J.E., Spicer, L., Zasada, I.A. (2010). Effects of organic amendment and tillage on soil microorganisms and microfauna. Applied Soil Ecology, 46: 103–110.

General studies of soil health and soil health indicators

Bastida, F., Zsolnay, A., Hernández, T., García, C. (2008). Past, present and future of soil quality indices: A biological perspective. *Geoderma*, 147: 159–171.

Cardoso, E.J.B.N., Vasconcellos, R.L.F., Bini, D., Miyauchi, M.Y. H, dos Santos, C.A., Alves, P.R. L., de Paula, A.M., Nakatani, A.S., de Moraes Pereira, J., Nogueira, M.A. (2013). Soil health: looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? *Scientia Agricola*, 70(4): 274-289.

de Bruyn L. L., and Andrews S. (2016). Are Australian and United States farmers using soil information for soil health management? *Sustainability*, 8: 304. doi:10.3390/su8040304

Garrigues, E., Corson, M.S., Angers, D.A., van der Werf, H.M.G., Walter, C. (2012). Soil quality in Life Cycle Assessment: Towards development of an indicator. *Ecological Indicators*, 18: 434–442.

Gregorich, E.G., Carter, M.R., Angers, D.A., Monreal, C.M., Ellert, B.H. (1994). Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Canadian Journal of Soil Research*, 74: 367-385.

Gonzalez-Quiñones, V., Stockdale, E.A., Banning, N.C., Hoyle, F.C., Sawada, Y., Wherrett, A.D., Jones, D.L., Murphy, D.V. (2011). Soil microbial biomass - Interpretation and consideration for soil monitoring. *Soil Research*, 49: 287–304.

Kaschuk, G., Alberton, O., Hungria, M. (2010). Three decades of soil microbial biomass studies in Brazilian ecosystems: Lessons learned about soil quality and indications for improving sustainability. *Soil Biology & Biochemistry*, 42: 1–13.

Liu, J., Wu, L., Chen, D., Li, M., Wei, C. (2017). Soil quality assessment of different Camellia oleifera stands in mid-subtropical China. *Applied Soil Ecology*, 113: 29–35.

Mueller, L., Schindler, U., Mirschel, W., Shepherd., T.G., Ball, B.C., Helming, K., Rogasik, J., Eulenstein, F., Wiggering., H. (2010). Assessing the productivity function of soils. A review. *Agronomy for Sustainable Development*, 30: 601–614.

Oberholzer, H.R., Freiermuth Knuchel, R., Weisskopf, P., Gaillard, G. (2012). A novel method for soil quality in life cycle assessment using several soil indicators. *Agronomy for Sustainable Development*, 32 (3): 639-649.

Reeve, J.R., Schadt, C.W., Carpenter-Boggs, L., Kang, S., Zhou, J. and Reganold, J.P. (2010). Effects of soil type and farm management on soil ecological functional genes and microbial activities. *International Society for Microbial Ecology Journal*, 4: 1099–1107.

Scholter, M., Dilly, O., Munch, J.C. (2003). Indicators for evaluating soil quality. *Agriculture, Ecosystems and Environment*, 98: 255–262.

Conservation agriculture

Henneron, L., Bernard, L., Hedde, M., Pelosi, C., Villenave, C., Chenu, C., Bertrand, M., Girardin, C., Blanchart, E. (2015). Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. *Agronomy for Sustainable Development*, 35: 169–181.

Larney, F.J., Pearson, D.C., Blackshaw, R.E., Lupwayi, N.Z. (2017). Soil changes over 12 yr of conventional vs. conservation management on irrigated rotations in southern Alberta. *Canadian Journal of Soil Science*, 97: 249–265. dx.doi.org/10.1139/cjss-2016-0141

Scopel, E., Triomphe, B., Affholder, F., Da Silva, F.A.M., Corbeels, M., Xavier, J. H.V., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E., de Carvalho Mendes, I., De Tourdonnet, S. (2013). Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. *Agronomy for Sustainable Development*, 33: 113. doi.org/10.1007/s13593-012-0106-9

Sithole, N. J., Magwaza, L. S., Mafongoya, P.L. (2016). Conservation agriculture and its impact on soil quality and maize yield: A South African perspective. *Soil & Tillage Research*, 162: 55–67.

Stavi, I., Bel, G., Zaady, E. (2016). Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review. *Agronomy for Sustainable Development*, 36: 32.

Cover crops

Abdalla, M, Rueangritsarakul, K, Jones M, Osborne, B, Helmy, M, Roth, B, Burke J, Nolan, P, Smith P, Williams, M (2012). How effective is reduced tillage–cover crop management in reducing N_2O fluxes from arable crop soils? *Water Air and Soil Pollution*, 223: 5155–5174.

Alvarez, R., Steinbach, H.S., De Paepa, J.L. (2017). Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis. *Soil & Tillage Research*, 170: 53–65

Brennan, E.B. and Acosta-Martinez, V. (2017). Cover cropping frequency is the main driver of soil microbial changes during six years of organic vegetable production. *Soil Biology & Biochemistry*, 109: 188-204.

Leslie, A.W., Wang, K.H., Meyer, S.L.F., Marahatta, S., Hooks, C.R.R. (2017). Influence of cover crops on arthropods, free-living nematodes, and yield in a succeeding no-till soybean crop. *Applied Soil Ecology*, 117–118: 21–31.

Nivelle, E., Verzeaux, J., Habbib, H., Kuzyakov, Y., Decocq, G., Roger, D., Lacoux, J., Duclercq, J., Spicher, F., Nava-Saucedo, J.E., Catterou,M., Dubois, F., Tetu, T. (2016). Functional response of soil microbial communities to tillage, cover crops and nitrogen fertilization. *Applied Soil Ecology*, 108: 147–155.

Crop residue removal/addition

Blanco-Canqui, H. and Lal, R. (2009). Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Science*, 28: 139–163.
doi: 10.1080/07352680902776507

Chen, H., Li X., Hu, F. and Shi, W. (2013). Soil nitrous oxide emissions following crop residue addition: a meta-analysis. *Global Change Biology*, 19: 2956–2964. doi: 10.1111/gcb.12274

Hiel, M.P., Chélin, M., Parvin, N., Barbieux, S., Degrune, F., Lemtiri, A., Colinet, G., Degré, A., Bodson, B., Garré, S. (2016). Crop residue management in arable cropping systems under temperate climate. Part 2: Soil physical properties and crop production. A review. *Biotechnology, Agronomy, Society and Environment*, 20(S1): 245-256.

Kong, L. (2014). Maize residues, soil quality, and wheat growth in China. A review. *Agronomy for Sustainable Development*, 34: 405–416.

Lu, X. and Lu, X. (2017). Tillage and crop residue effects on the energy consumption,

input–output costs and greenhouse gas emissions of maize crops. *Nutrient Cycling in Agroecosystems*, 08: 323–337.

Rotations/multi cropping

Crotty, F.V., Fychan, R., Sanderson, R., Rhymes, J.R., Bourdin, F., Scullion, J., Marley, C.L. (2016). Understanding the legacy effect of previous forage crop and tillage management on soil biology, after conversion to an arable crop rotation. *Soil Biology & Biochemistry*, 103: 241-252.

Dias, T., Dukes, A., Antunes, P.M. (2015). Accounting for soil biotic effects on soil health and crop productivity in the design of crop rotations. *Journal of the Science of Food and Agriculture*, 95: 447–454.

Ehrmann, J. and Ritz, K. (2014). Plant: soil interactions in temperate multi-cropping production systems. *Plant and Soil*, 376: 1–29.

Halvorson, J. J., Liebig , M. A., Archer, D.W., West, M.S., Tanaka, D.L. (2016). Impacts of crop sequence and tillage management on soil carbon stocks in south-central North Dakota. *Soil Science Society of America Journal*, 80: 1003–1010.

Nakajima, T., Shrestha, R.K., Lal, R. (2016). On-farm assessments of soil quality in Ohio and Michigan. *Soil Science Society of America Journal*, 80: 1020–1026.

Earthworms

Bartz, M.L.C., Pasini, A., Brown, G.G. (2013). Earthworms as soil quality indicators in Brazilian no-tillage systems. *Applied Soil Ecology*, 69: 39-48.

Bertrand, M., Barot, S., Blouin, M., Whalen, J., de Oliveira, T., Roger-Estrade, J. (2015). Earthworm services for cropping systems. A review. *Agronomy for Sustainable Development*, 35: 553–567.

Lorenz, K., and Lal, R. (2016). Environmental impact of organic agriculture. *Advances in Agronomy*, 88: 35-56.

van Groenigen, J.W., Lubbers, I.M., Vos, H.M.J., Brown, G.G., De Deyn, G.B., van Groenigen, K.J. (2014). Earthworms increase plant production: a meta-analysis. *Scientific Reports*, 4: 6365.

Fertiliser/herbicides

Ludwig, B., Geisseler, D., Michel, K., Joergensen, R.G., Schulz, E., Merbach I., Raupp, J., Rauber, Hu, K., Niu, L., Liu, X. (2011). Effects of fertilization and soil management on crop yields and carbon stabilization in soils. A review. *Agronomy for Sustainable Development*, 31: 361–372.

Lupwayi, N.Z., Brandt, S.A., Harker, K.N., O'Donovan, J.T., Clayton, G.W., Turkington, T.K. (2010). Contrasting soil microbial responses to fertilizers and herbicides in a canola barley rotation. *Soil Biology & Biochemistry*, 42: 1997-2004.

Nivelle, E., Verzeaux, J., Habbib, H., Kuzyakov, Y., Decocq, G., Roger, D., Lacoux, J., Duclercq, J., Spicher, F., Nava-Saucedo, J.E., Catterou,M., Dubois, F., Tetu, T. (2016). Functional response of soil microbial communities to tillage, cover crops and nitrogen fertilization. *Applied Soil Ecology*, 108: 147–155.

Nguyen, D.B., Rose, M.T., Rose, T.J., Morris, S.G., Zwieten, L.V. (2016). Impact of glyphosate on soil microbial biomass and respiration: a meta-analysis. *Soil Biology & Biochemistry*, 92: 50-57.

Soil biodiversity

Ferris, H. and Tuomisto, H. (2015). Unearthing the role of biological diversity in soil health. *Soil Biology & Biochemistry*, 85: 101-109.

Lehman, R.M., Cambardella, C.A., Stott, D.E., Acosta-Martinez, V., Daniel K. Manter, D.K., Buyer, J.S., Maul, J.E., Smith, J.L., Collins, H.P., Halvorson, J.J., Kremer, R.J., Lundgren, J.G., Ducey, T.F., Jin, V.L., Karlen, D.L. (2015). Understanding and enhancing soil biological health: The solution for reversing soil degradation. *Sustainability*, 7: 988-1027.

Lemanceau, P., Maron, P.A., Mazurier, S., Mougel, C., Pivato, B., Plassart, P., Ranjard, L., Revellin, C., Tardy, V., Wipf, D. (2015). Understanding and managing soil biodiversity: a major challenge in agroecology. *Agronomy for Sustainable Development*, 35: 67–81.

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., Rutgers, M. (2012). Soil biodiversity, biological indicators and soil ecosystem services—an overview of European approaches. *Current Opinion in Environmental Sustainability*, 4: 529–538.

Disease/Pest control

Ghorbani, R., Wilcockson, S., Koocheki, A., Leifert, C. (2008). Soil management for sustainable crop disease control: a review. *Environmental Chemistry Letters*, 6: 149–162.

Hodson, A. and Lewis, E. (2016). Managing for soil health can suppress pests. California Agriculture, 70(3): 137-141.

Larkin, R.P. (2015). Soil health paradigms and implications for disease management. *Annual Review of Phytopathology*, 53: 199–221.

Plant species diversity

Chaparro, J.M., Sheflin, A,M., Manter, D.K., Vivanco, J.M. (2012). Manipulating the soil microbiome to increase soil health and plant fertility. *Biology and Fertility of Soils*, 48: 489–499.

Huang, L.F., Song, L.X., Xia, X.J., Mao, W.H, Shi, K., Zhou, Y.H., Yu, J.Q. (2013). Plant-soil feedbacks and soil sickness: From mechanisms to application in agriculture. *Journal of Chemical Ecology*, 39: 232–242.

Mitter, B., Brader, G., Afzal, M., Compant, S., Naveed, M., Trognitz, F., Sessitsch, A. (2013). Advances in elucidating beneficial interactions between plants, soil, and bacteria. *Advances in Agronomy*, 121: 381-445.

General management effects

Indoria, A.K., Sharma, K. L., Sammi Reddy, K., Srinivasa Rao, Ch. (2016). Role of soil physical properties in soil health management and crop productivity in rainfed systems–II. Management technologies and crop productivity. *Current Science*, 110(3): 320-328.

Ludwig, B., Geisseler, D., Michel, K., Joergensen, R.G., Schulz, E., Merbach I., Raupp, J., Rauber, Hu, K., Niu, L., Liu, X. (2011). Effects of fertilization and soil management on crop yields and carbon stabilization in soils. A review. *Agronomy for Sustainable Development*, 31: 361–372.

Plastic Mulch

Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., Muñozc, K., Frör, O., Schaumann, G.E. (2016). Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? *Science of the Total Environment*, 550: 690–705.

Muñoz, K., Buchmann, C., Meyer, M., Schmidt-Heydt, M., Steinmetz, Z., Diehl, D., Thiele-Bruhn, S., Schaumann, G.E. (2017). Physicochemical and microbial soil quality indicators as affected by the agricultural management system in strawberry cultivation using straw or black polyethylene mulching. *Applied Soil Ecology*, 113: 36–44.
doi: 10.1016/j.apsoil.2017.01.014

Soil degradation

Baumhardt, R.L., Stewart, B.A., Sainju, U.M. (2015). North American soil degradation: Processes, practices, and mitigating strategies. *Sustainability*, 7: 2936-2960. doi:10.3390/su7032936

Bennett, L.T., Mele, P.M., Annett, S., Kasel, S. (2010). Examining links between soil management, soil health, and public benefits in agricultural landscapes: An Australian perspective. *Agriculture, Ecosystems and Environment*, 139: 1–12.

Biochar

McCormack, S.A., Ostle, N., Bardgett, R.D., Hopkins, D.W., Vanbergen, A.J. (2013). Biochar in bioenergy cropping systems: Impacts on soil faunal communities and linked ecosystem processes. *Global Change Biology Bioenergy*, 5: 81–95.
doi: 10.1111/gcbb.12046

Carbon sequestration

Ostle, N.J., Levy, P.E., Evans, C.D., Smith, P. (2009). UK land use and soil carbon sequestration. *Land Use Policy*, 26S: S274–S283.

Drainage

Ballantine, D.J., Tanner, C.C. (2013). Controlled drainage systems to reduce contaminant losses and optimize productivity from New Zealand pastoral systems. *New Zealand Journal of Agricultural Research*, 56(2): 171-185. DOI: 10.1080/00288233.2013.781509

Compaction

Batey, T. (2009). Soil compaction and soil management – a review. *Soil Use and Management*, 25: 335–345.

Water quality

Kay, P., Edwards, A.C., Foulger, M. (2009). A review of the efficacy of contemporary agricultural stewardship measures for ameliorating water pollution problems of key concern to the UK water industry. *Agricultural Systems*, 99: 67–75.

7.2. Appendix 2. Table to show how the soil health indicators are affected by management options and farm attributes

Table to show how the soil health indicators (biological, chemical, physical and yield) are affected: firstly by management options of reduced tillage, a carbon-rich organic matter addition (Hi C OM), a nitrogen-rich organic matter addition (Hi N OM) or a cover crop; then how the soil health indicators are moderated by individual farm attributes of soil type (sand, medium and clay), climate (cold and wet, cold and dry, warm and wet, warm and dry) and cropping system (a combinable arable system with no root crops, a combinable arable system with root crops or predominantly grass); and finally how the soil health indicators would be moderated by combinations of the farm attributes.

Soil health indicator																							
	Biology									**Chemistry**									**Physics**			**Yield**
	Earthworms	**Microbial biomass**	**Enzymes/activity**	**Natural enemies**	**Mycorrhyzae**	**Soil biota**	**Fewer slugs**	**Fewer weeds**	**Less disease**	**SOM**	**N**	**P**	**K**	**pH**	**CEC**	**Less nutrient loss**	**Lees herbicide use**	**Nutrient availability**	**Infiltration**	**Trafficability**	**Structure**	**Yield**
Management option (direction of effect)																						
reduced tillage	+	+	+	+	+	+	-	-	-	+	=	=	=	=	=	+	-	=	-	+	+	-
Hi C OM	+	+	+	+	=	+	=	=	=	+	=	=	+	=	+	-	=	-	+	+	+	+
Hi N OM	=	+	=	+	=	+	=	=	=	+	=	+	=	=	=	-	=	-	=	=	=	+
cover crop	+	+	+	+	+	+	=	+	=	+	+	=	=	=	=	+	=	=	=	=	=	=
Management option (numerical effect)																						
reduced tillage	1	1	1	1	1	1	-1	-1	-1	1	0	0	0	0	0	1	-1	0	-1	1	1	-1
Hi C OM	1	1	1	1	0	1	0	0	0	1	0	0	1	0	1	-1	0	-1	1	1	1	1
Hi N OM	0	1	0	1	0	1	0	0	0	1	0	1	0	0	0	-1	0	-1	0	0	0	1
cover crop	1	1	1	1	1	1	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0

Moderating effect of farm attributes - from Table 2																						
sand (s)	-1	-1	1	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	-1	1	1	-1	-1
medium (m)	0	0	1	0	0	1	-1	-1	-1	0	0	0	0	0	0	-1	0	0	0	0	1	0
clay (c)	1	1	0	0	0	0	0	-1	-1	1	1	0	1	0	1	0	0	1	0	-1	1	1
cold/wet (cw)	0	0	0	0	0	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0	-1	0	0
cold/dry (cd)	-1	-1	0	-1	-1	-1	-1	-1	-1	1	0	0	0	0	0	-1	0	0	0	0	0	-1
warm/wet (ww)	1	1	1	1	1	1	1	-1	1	1	0	0	0	0	0	1	0	0	0	-1	0	1
warm/dry (wd)	-1	-1	1	-1	-1	-1	0	-1	1	-1	-1	0	0	0	0	-1	0	0	0	1	0	0
arable-combinable (ac)	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
arable-roots (ar)	-1	0	0	-1	-1	-1	0	0	0	-1	-1	0	0	0	0	1	0	0	0	0	0	0
grass (gr)	1	1	1	1	1	1	0	-1	0	1	0	0	0	0	0	-1	-1	0	1	1	1	0
Moderating effects of combinations of farm attributes																						
s cw ac	-1	-1	1	0	0	0	-1	-2	-2	-1	-1	-1	-1	-1	-1	0	0	-1	1	0	-1	-1
s cw ar	-2	-1	1	-1	-1	-1	-1	-2	-2	-1	-1	-1	-1	-1	-1	1	0	-1	1	0	-1	-1
s cw gr	0	0	2	1	1	1	-1	-3	-2	1	0	-1	-1	-1	-1	-1	-1	-1	2	1	0	-1
s cd ac	-2	-2	1	-1	-1	-1	-2	-2	-2	-1	-2	-1	-1	-1	-1	-1	0	-1	1	1	-1	-2
s cd ar	-3	-2	1	-2	-2	-2	-2	-2	-2	-1	-2	-1	-1	-1	-1	0	0	-1	1	1	-1	-2
s cd gr	-1	-1	2	0	0	0	-2	-3	-2	1	-1	-1	-1	-1	-1	-2	-1	-1	2	2	0	-2
s ww ac	0	0	2	1	1	1	0	-2	0	-1	-2	-1	-1	-1	-1	1	0	-1	1	0	-1	0
s ww ar	-1	0	2	0	0	0	0	-2	0	-1	-2	-1	-1	-1	-1	2	0	-1	1	0	-1	0
s ww gr	1	1	3	2	2	2	0	-3	0	1	-1	-1	-1	-1	-1	0	-1	-1	2	1	0	0
s wd ac	-2	-2	2	-1	-1	-1	-1	-2	0	-3	-3	-1	-1	-1	-1	-1	0	-1	1	2	-1	-1
s wd ar	-3	-2	2	-2	-2	-2	-1	-2	0	-3	-3	-1	-1	-1	-1	0	0	-1	1	2	-1	-1
s wd gr	-1	-1	3	0	0	0	-1	-3	0	-1	-2	-1	-1	-1	-1	-2	-1	-1	2	3	0	-1

m cw ac	0	0	1	0	0	1	-1	-2	-2	0	0	0	0	0	0	-1	0	0	0	-1	1	0
m cw ar	-1	0	1	-1	-1	0	-1	-2	-2	0	0	0	0	0	0	0	0	0	0	-1	1	0
m cw gr	1	1	2	1	1	2	-1	-3	-2	2	1	0	0	0	0	-2	-1	0	1	0	2	0
m cd ac	-1	-1	1	-1	-1	0	-2	-2	-2	0	-1	0	0	0	0	-2	0	0	0	0	1	-1
m cd ar	-2	-1	1	-2	-2	-1	-2	-2	-2	0	-1	0	0	0	0	-1	0	0	0	0	1	-1
m cd gr	0	0	2	0	0	1	-2	-3	-2	2	0	0	0	0	0	-3	-1	0	1	1	2	-1
m ww ac	1	1	2	1	1	2	0	-2	0	0	-1	0	0	0	0	0	0	0	0	-1	1	1
m ww ar	0	1	2	0	0	1	0	-2	0	0	-1	0	0	0	0	1	0	0	0	-1	1	1
m ww gr	2	2	3	2	2	3	0	-3	0	2	0	0	0	0	0	-1	-1	0	1	0	2	1
m wd ac	-1	-1	2	-1	-1	0	-1	-2	0	-2	-2	0	0	0	0	-2	0	0	0	1	1	0
m wd ar	-2	-1	2	-2	-2	-1	-1	-2	0	-2	-2	0	0	0	0	-1	0	0	0	1	1	0
m wd gr	0	0	3	0	0	1	-1	-3	0	0	-1	0	0	0	0	-3	-1	0	1	2	2	0
c cw ac	1	1	0	0	0	0	0	-2	-2	1	1	0	1	0	1	0	0	1	0	-2	1	1
c cw ar	0	1	0	-1	-1	-1	0	-2	-2	1	1	0	1	0	1	1	0	1	0	-2	1	1
c cw gr	2	2	1	1	1	1	0	-3	-2	3	2	0	1	0	1	-1	-1	1	1	-1	2	1
c cd ac	0	0	0	-1	-1	-1	-1	-2	-2	1	0	0	1	0	1	-1	0	1	0	-1	1	0
c cd ar	-1	0	0	-2	-2	-2	-1	-2	-2	1	0	0	1	0	1	0	0	1	0	-1	1	0
c cd gr	1	1	1	0	0	0	-1	-3	-2	3	1	0	1	0	1	-2	-1	1	1	0	2	0
c ww ac	2	2	1	1	1	1	1	-2	0	1	0	0	1	0	1	1	0	1	0	-2	1	2
c ww ar	1	2	1	0	0	0	1	-2	0	1	0	0	1	0	1	2	0	1	0	-2	1	2
c ww gr	3	3	2	2	2	2	1	-3	0	3	1	0	1	0	1	0	-1	1	1	-1	2	2
cwd ac	0	0	1	-1	-1	-1	0	-2	0	-1	-1	0	1	0	1	-1	0	1	0	0	1	1
c wd ar	-1	0	1	-2	-2	-2	0	-2	0	-1	-1	0	1	0	1	0	0	1	0	0	1	1
c wd gr	1	1	2	0	0	0	0	-3	0	1	0	0	1	0	1	-2	-1	1	1	1	2	1

7.3. Appendix 3. Tables showing how the soil health indicators would be modified by combinations of the farm attributes and the numerical range of those modifiers

Table showing firstly: how the soil health indicators that are reported in the calculator would be moderated by combinations of the farm attributes and the numerical range of those modifiers. For the calculator: (1) earthworms, microbial biomass, soil enzyme and microbial activity; natural enemies, mycorrhiza and soil biota have been combined into the category 'positive biology'; (2) nutrient loss (i.e. nitrogenous leaching, run-off, gaseous emissions) and nutrient availability (degree of nitrogen immobilisation) are combined as 'nutrient use'; The numerical values are then normalised to account for the different ranges obtained; finally the effects of various management options (no-tillage, carbon-rich organic matter, nitrogen-rich organic matter, cover crop and reduced tillage (75% of the effect of no-tillage, Peigné *et al*., 2007) on soil health indicators depending on the combination of farm attributes are presented.

Moderating effects of combinations of farm attributes - for the indicators to be reported in the calculator															
	Positive biology	**Fewer slugs**	**Fewer weeds**	**Less disease**	**SOM**	**N**	**P**	**K**	**CEC**	**Nutrient use**	**Less herbicide**	**Water Infiltration**	**Trafficability**	**Soil Structure**	**Yield**
s cw ac	-1	-1	-2	-2	-1	-1	-1	-1	-1	-1	0	1	0	-1	-1
s cw ar	-5	-1	-2	-2	-1	-1	-1	-1	-1	0	0	1	0	-1	-1
s cw gr	5	-1	-3	-2	1	0	-1	-1	-1	-2	-1	2	1	0	-1
s cd ac	-6	-2	-2	-2	-1	-2	-1	-1	-1	-2	0	1	1	-1	-2
s cd ar	-10	-2	-2	-2	-1	-2	-1	-1	-1	-1	0	1	1	-1	-2
s cd gr	0	-2	-3	-2	1	-1	-1	-1	-1	-3	-1	2	2	0	-2
s ww ac	5	0	-2	0	-1	-2	-1	-1	-1	0	0	1	0	-1	0
s ww ar	1	0	-2	0	-1	-2	-1	-1	-1	1	0	1	0	-1	0
s ww gr	11	0	-3	0	1	-1	-1	-1	-1	-1	-1	2	1	0	0
s wd ac	-5	-1	-2	0	-3	-3	-1	-1	-1	-2	0	1	2	-1	-1
s wd ar	-9	-1	-2	0	-3	-3	-1	-1	-1	-1	0	1	2	-1	-1
s wd gr	1	-1	-3	0	-1	-2	-1	-1	-1	-3	-1	2	3	0	-1

m cw ac	2	-1	-2	-2	0	0	0	0	0	-1	0	0	-1	1	0
m cw ar	-2	-1	-2	-2	0	0	0	0	0	0	0	0	-1	1	0
m cw gr	8	-1	-3	-2	2	1	0	0	0	-2	-1	1	0	2	0
m cd ac	-3	-2	-2	-2	0	-1	0	0	0	-2	0	0	0	1	-1
m cd ar	-7	-2	-2	-2	0	-1	0	0	0	-1	0	0	0	1	-1
m cd gr	3	-2	-3	-2	2	0	0	0	0	-3	-1	1	1	2	-1
m ww ac	8	0	-2	0	0	-1	0	0	0	0	0	0	-1	1	1
m ww ar	4	0	-2	0	0	-1	0	0	0	1	0	0	-1	1	1
m ww gr	14	0	-3	0	2	0	0	0	0	-1	-1	1	0	2	1
m wd ac	-2	-1	-2	0	-2	-2	0	0	0	-2	0	0	1	1	0
m wd ar	-6	-1	-2	0	-2	-2	0	0	0	-1	0	0	1	1	0
m wd gr	4	-1	-3	0	0	-1	0	0	0	-3	-1	1	2	2	0
c cw ac	2	0	-2	-2	1	1	0	1	1	1	0	0	-2	1	1
c cw ar	-2	0	-2	-2	1	1	0	1	1	2	0	0	-2	1	1
c cw gr	8	0	-3	-2	3	2	0	1	1	0	-1	1	-1	2	1
c cd ac	-3	-1	-2	-2	1	0	0	1	1	0	0	0	-1	1	0
c cd ar	-7	-1	-2	-2	1	0	0	1	1	1	0	0	-1	1	0
c cd gr	3	-1	-3	-2	3	1	0	1	1	-1	-1	1	0	2	0
c ww ac	8	1	-2	0	1	0	0	1	1	2	0	0	-2	1	2
c ww ar	4	1	-2	0	1	0	0	1	1	3	0	0	-2	1	2
c ww gr	14	1	-3	0	3	1	0	1	1	1	-1	1	-1	2	2
cwd ac	-2	0	-2	0	-1	-1	0	1	1	0	0	0	0	1	1
c wd ar	-6	0	-2	0	-1	-1	0	1	1	1	0	0	0	1	1
c wd gr	4	0	-3	0	1	0	0	1	1	-1	-1	1	1	2	1
Range	18 to -18	3 to -3	3 to -3	3 to -3	3 to -3	3 to -3	3 to -3	3 to -3	3 to -3	6 to -6	3 to -3	3 to -3	3 to -3	3 to -3	3 to -3

Numerical modifier to normalise for the range of combined attributes															
	Positive biology	Fewer slugs	Fewer weeds	Less disease	SOM	N	P	K	CEC	Nutrient use	Less herbicide	Water Infiltration	Trafficability	Soil Structure	Yield
s cw ac	-0.02	-0.10	-0.20	-0.20	-0.10	-0.10	-0.10	-0.10	-0.10	-0.05	0.00	0.10	0.00	-0.10	-0.10
s cw ar	-0.08	-0.10	-0.20	-0.20	-0.10	-0.10	-0.10	-0.10	-0.10	0.00	0.00	0.10	0.00	-0.10	-0.10
s cw gr	0.08	-0.10	-0.30	-0.20	0.10	0.00	-0.10	-0.10	-0.10	-0.10	-0.10	0.20	0.10	0.00	-0.10
s cd ac	-0.10	-0.20	-0.20	-0.20	-0.10	-0.20	-0.10	-0.10	-0.10	-0.10	0.00	0.10	0.10	-0.10	-0.20
s cd ar	-0.17	-0.20	-0.20	-0.20	-0.10	-0.20	-0.10	-0.10	-0.10	-0.05	0.00	0.10	0.10	-0.10	-0.20
s cd gr	0.00	-0.20	-0.30	-0.20	0.10	-0.10	-0.10	-0.10	-0.10	-0.15	-0.10	0.20	0.20	0.00	-0.20
s ww ac	0.08	0.00	-0.20	0.00	-0.10	-0.20	-0.10	-0.10	-0.10	0.00	0.00	0.10	0.00	-0.10	0.00
s ww ar	0.02	0.00	-0.20	0.00	-0.10	-0.20	-0.10	-0.10	-0.10	0.05	0.00	0.10	0.00	-0.10	0.00
s ww gr	0.18	0.00	-0.30	0.00	0.10	-0.10	-0.10	-0.10	-0.10	-0.05	-0.10	0.20	0.10	0.00	0.00
s wd ac	-0.08	-0.10	-0.20	0.00	-0.30	-0.30	-0.10	-0.10	-0.10	-0.10	0.00	0.10	0.20	-0.10	-0.10
s wd ar	-0.15	-0.10	-0.20	0.00	-0.30	-0.30	-0.10	-0.10	-0.10	-0.05	0.00	0.10	0.20	-0.10	-0.10
s wd gr	0.02	-0.10	-0.30	0.00	-0.10	-0.20	-0.10	-0.10	-0.10	-0.15	-0.10	0.20	0.30	0.00	-0.10
m cw ac	0.03	-0.10	-0.20	-0.20	0.00	0.00	0.00	0.00	0.00	-0.05	0.00	0.00	-0.10	0.10	0.00
m cw ar	-0.03	-0.10	-0.20	-0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	0.10	0.00
m cw gr	0.13	-0.10	-0.30	-0.20	0.20	0.10	0.00	0.00	0.00	-0.10	-0.10	0.10	0.00	0.20	0.00
m cd ac	-0.05	-0.20	-0.20	-0.20	0.00	-0.10	0.00	0.00	0.00	-0.10	0.00	0.00	0.00	0.10	-0.10
m cd ar	-0.12	-0.20	-0.20	-0.20	0.00	-0.10	0.00	0.00	0.00	-0.05	0.00	0.00	0.00	0.10	-0.10
m cd gr	0.05	-0.20	-0.30	-0.20	0.20	0.00	0.00	0.00	0.00	-0.15	-0.10	0.10	0.10	0.20	-0.10
m ww ac	0.13	0.00	-0.20	0.00	0.00	-0.10	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	0.10	0.10
m ww ar	0.07	0.00	-0.20	0.00	0.00	-0.10	0.00	0.00	0.00	0.05	0.00	0.00	-0.10	0.10	0.10
m ww gr	0.23	0.00	-0.30	0.00	0.20	0.00	0.00	0.00	0.00	-0.05	-0.10	0.10	0.00	0.20	0.10
m wd ac	-0.03	-0.10	-0.20	0.00	-0.20	-0.20	0.00	0.00	0.00	-0.10	0.00	0.00	0.10	0.10	0.00
m wd ar	-0.10	-0.10	-0.20	0.00	-0.20	-0.20	0.00	0.00	0.00	-0.05	0.00	0.00	0.10	0.10	0.00
m wd gr	0.07	-0.10	-0.30	0.00	0.00	-0.10	0.00	0.00	0.00	-0.15	-0.10	0.10	0.20	0.20	0.00
c cw ac	0.03	0.00	-0.20	-0.20	0.10	0.10	0.00	0.10	0.10	0.05	0.00	0.00	-0.20	0.10	0.10

c cw ar	-0.03	0.00	-0.20	-0.20	0.10	0.10	0.00	0.10	0.10	0.10	0.00	0.00	-0.20	0.10	0.10
c cw gr	0.13	0.00	-0.30	-0.20	0.30	0.20	0.00	0.10	0.10	0.00	-0.10	0.10	-0.10	0.20	0.10
c cd ac	-0.05	-0.10	-0.20	-0.20	0.10	0.00	0.00	0.10	0.10	0.00	0.00	0.00	-0.10	0.10	0.00
c cd ar	-0.12	-0.10	-0.20	-0.20	0.10	0.00	0.00	0.10	0.10	0.05	0.00	0.00	-0.10	0.10	0.00
c cd gr	0.05	-0.10	-0.30	-0.20	0.30	0.10	0.00	0.10	0.10	-0.05	-0.10	0.10	0.00	0.20	0.00
c ww ac	0.13	0.10	-0.20	0.00	0.10	0.00	0.00	0.10	0.10	0.10	0.00	0.00	-0.20	0.10	0.20
c ww ar	0.07	0.10	-0.20	0.00	0.10	0.00	0.00	0.10	0.10	0.15	0.00	0.00	-0.20	0.10	0.20
c ww gr	0.23	0.10	-0.30	0.00	0.30	0.10	0.00	0.10	0.10	0.05	-0.10	0.10	-0.10	0.20	0.20
cwd ac	-0.03	0.00	-0.20	0.00	-0.10	-0.10	0.00	0.10	0.10	0.00	0.00	0.00	0.00	0.10	0.10
c wd ar	-0.10	0.00	-0.20	0.00	-0.10	-0.10	0.00	0.10	0.10	0.05	0.00	0.00	0.00	0.10	0.10
c wd gr	0.07	0.00	-0.30	0.00	0.10	0.00	0.00	0.10	0.10	-0.05	-0.10	0.10	0.10	0.20	0.10

Effect of management option according to farm attributes															
No-tillage	**Positive biology**	**Fewer slugs**	**Fewer weeds**	**Less disease**	**SOM**	**N**	**P**	**K**	**CEC**	**Nutrient use**	**Less herbicide**	**Water Infiltration**	**Trafficability**	**Soil Structure**	**Yield**
s cw ac	0.98	-1.10	-1.20	-1.20	0.90	-0.10	-0.10	-0.10	-0.10	0.45	-1.00	-0.90	1.00	0.90	-1.10
s cw ar	0.92	-1.10	-1.20	-1.20	0.90	-0.10	-0.10	-0.10	-0.10	0.50	-1.00	-0.90	1.00	0.90	-1.10
s cw gr	1.08	-1.10	-1.30	-1.20	1.10	0.00	-0.10	-0.10	-0.10	0.40	-1.10	-0.80	1.10	1.00	-1.10
s cd ac	0.90	-1.20	-1.20	-1.20	0.90	-0.20	-0.10	-0.10	-0.10	0.40	-1.00	-0.90	1.10	0.90	-1.20
s cd ar	0.83	-1.20	-1.20	-1.20	0.90	-0.20	-0.10	-0.10	-0.10	0.45	-1.00	-0.90	1.10	0.90	-1.20
s cd gr	1.00	-1.20	-1.30	-1.20	1.10	-0.10	-0.10	-0.10	-0.10	0.35	-1.10	-0.80	1.20	1.00	-1.20
s ww ac	1.08	-1.00	-1.20	-1.00	0.90	-0.20	-0.10	-0.10	-0.10	0.50	-1.00	-0.90	1.00	0.90	-1.00
s ww ar	1.02	-1.00	-1.20	-1.00	0.90	-0.20	-0.10	-0.10	-0.10	0.55	-1.00	-0.90	1.00	0.90	-1.00
s ww gr	1.18	-1.00	-1.30	-1.00	1.10	-0.10	-0.10	-0.10	-0.10	0.45	-1.10	-0.80	1.10	1.00	-1.00
s wd ac	0.92	-1.10	-1.20	-1.00	0.70	-0.30	-0.10	-0.10	-0.10	0.40	-1.00	-0.90	1.20	0.90	-1.10
s wd ar	0.85	-1.10	-1.20	-1.00	0.70	-0.30	-0.10	-0.10	-0.10	0.45	-1.00	-0.90	1.20	0.90	-1.10
s wd gr	1.02	-1.10	-1.30	-1.00	0.90	-0.20	-0.10	-0.10	-0.10	0.35	-1.10	-0.80	1.30	1.00	-1.10
m cw ac	1.03	-1.10	-1.20	-1.20	1.00	0.00	0.00	0.00	0.00	0.45	-1.00	-1.00	0.90	1.10	-1.00
m cw ar	0.97	-1.10	-1.20	-1.20	1.00	0.00	0.00	0.00	0.00	0.50	-1.00	-1.00	0.90	1.10	-1.00
m cw gr	1.13	-1.10	-1.30	-1.20	1.20	0.10	0.00	0.00	0.00	0.40	-1.10	-0.90	1.00	1.20	-1.00
m cd ac	0.95	-1.20	-1.20	-1.20	1.00	-0.10	0.00	0.00	0.00	0.40	-1.00	-1.00	1.00	1.10	-1.10
m cd ar	0.88	-1.20	-1.20	-1.20	1.00	-0.10	0.00	0.00	0.00	0.45	-1.00	-1.00	1.00	1.10	-1.10
m cd gr	1.05	-1.20	-1.30	-1.20	1.20	0.00	0.00	0.00	0.00	0.35	-1.10	-0.90	1.10	1.20	-1.10
m ww ac	1.13	-1.00	-1.20	-1.00	1.00	-0.10	0.00	0.00	0.00	0.50	-1.00	-1.00	0.90	1.10	-0.90
m ww ar	1.07	-1.00	-1.20	-1.00	1.00	-0.10	0.00	0.00	0.00	0.55	-1.00	-1.00	0.90	1.10	-0.90
m ww gr	1.23	-1.00	-1.30	-1.00	1.20	0.00	0.00	0.00	0.00	0.45	-1.10	-0.90	1.00	1.20	-0.90
m wd ac	0.97	-1.10	-1.20	-1.00	0.80	-0.20	0.00	0.00	0.00	0.40	-1.00	-1.00	1.10	1.10	-1.00
m wd ar	0.90	-1.10	-1.20	-1.00	0.80	-0.20	0.00	0.00	0.00	0.45	-1.00	-1.00	1.10	1.10	-1.00
m wd gr	1.07	-1.10	-1.30	-1.00	1.00	-0.10	0.00	0.00	0.00	0.35	-1.10	-0.90	1.20	1.20	-1.00

c cw ac	1.03	-1.00	-1.20	-1.20	1.10	0.10	0.00	0.10	0.10	0.55	-1.00	-1.00	0.80	1.10	-0.90
c cw ar	0.97	-1.00	-1.20	-1.20	1.10	0.10	0.00	0.10	0.10	0.60	-1.00	-1.00	0.80	1.10	-0.90
c cw gr	1.13	-1.00	-1.30	-1.20	1.30	0.20	0.00	0.10	0.10	0.50	-1.10	-0.90	0.90	1.20	-0.90
c cd ac	0.95	-1.10	-1.20	-1.20	1.10	0.00	0.00	0.10	0.10	0.50	-1.00	-1.00	0.90	1.10	-1.00
c cd ar	0.88	-1.10	-1.20	-1.20	1.10	0.00	0.00	0.10	0.10	0.55	-1.00	-1.00	0.90	1.10	-1.00
c cd gr	1.05	-1.10	-1.30	-1.20	1.30	0.10	0.00	0.10	0.10	0.45	-1.10	-0.90	1.00	1.20	-1.00
c ww ac	1.13	-0.90	-1.20	-1.00	1.10	0.00	0.00	0.10	0.10	0.60	-1.00	-1.00	0.80	1.10	-0.80
c ww ar	1.07	-0.90	-1.20	-1.00	1.10	0.00	0.00	0.10	0.10	0.65	-1.00	-1.00	0.80	1.10	-0.80
c ww gr	1.23	-0.90	-1.30	-1.00	1.30	0.10	0.00	0.10	0.10	0.55	-1.10	-0.90	0.90	1.20	-0.80
cwd ac	0.97	-1.00	-1.20	-1.00	0.90	-0.10	0.00	0.10	0.10	0.50	-1.00	-1.00	1.00	1.10	-0.90
c wd ar	0.90	-1.00	-1.20	-1.00	0.90	-0.10	0.00	0.10	0.10	0.55	-1.00	-1.00	1.00	1.10	-0.90
c wd gr	1.07	-1.00	-1.30	-1.00	1.10	0.00	0.00	0.10	0.10	0.45	-1.10	-0.90	1.10	1.20	-0.90

High C organic matter	Positive biology	Fewer slugs	Fewer weeds	Less disease	SOM	N	P	K	CEC	Nutrient use	Less herbicide	Water Infiltration	Trafficability	Soil Structure	Yield
s cw ac	0.82	-0.10	-0.20	-0.20	0.90	-0.10	-0.10	0.90	0.90	-1.05	0.00	1.10	1.00	0.90	0.90
s cw ar	0.75	-0.10	-0.20	-0.20	0.90	-0.10	-0.10	0.90	0.90	-1.00	0.00	1.10	1.00	0.90	0.90
s cw gr	0.92	-0.10	-0.30	-0.20	1.10	0.00	-0.10	0.90	0.90	-1.10	-0.10	1.20	1.10	1.00	0.90
s cd ac	0.73	-0.20	-0.20	-0.20	0.90	-0.20	-0.10	0.90	0.90	-1.10	0.00	1.10	1.10	0.90	0.80
s cd ar	0.67	-0.20	-0.20	-0.20	0.90	-0.20	-0.10	0.90	0.90	-1.05	0.00	1.10	1.10	0.90	0.80
s cd gr	0.83	-0.20	-0.30	-0.20	1.10	-0.10	-0.10	0.90	0.90	-1.15	-0.10	1.20	1.20	1.00	0.80
s ww ac	0.92	0.00	-0.20	0.00	0.90	-0.20	-0.10	0.90	0.90	-1.00	0.00	1.10	1.00	0.90	1.00
s ww ar	0.85	0.00	-0.20	0.00	0.90	-0.20	-0.10	0.90	0.90	-0.95	0.00	1.10	1.00	0.90	1.00
s ww gr	1.02	0.00	-0.30	0.00	1.10	-0.10	-0.10	0.90	0.90	-1.05	-0.10	1.20	1.10	1.00	1.00
s wd ac	0.75	-0.10	-0.20	0.00	0.70	-0.30	-0.10	0.90	0.90	-1.10	0.00	1.10	1.20	0.90	0.90
s wd ar	0.68	-0.10	-0.20	0.00	0.70	-0.30	-0.10	0.90	0.90	-1.05	0.00	1.10	1.20	0.90	0.90
s wd gr	0.85	-0.10	-0.30	0.00	0.90	-0.20	-0.10	0.90	0.90	-1.15	-0.10	1.20	1.30	1.00	0.90
m cw ac	0.87	-0.10	-0.20	-0.20	1.00	0.00	0.00	1.00	1.00	-1.05	0.00	1.00	0.90	1.10	1.00
m cw ar	0.80	-0.10	-0.20	-0.20	1.00	0.00	0.00	1.00	1.00	-1.00	0.00	1.00	0.90	1.10	1.00
m cw gr	0.97	-0.10	-0.30	-0.20	1.20	0.10	0.00	1.00	1.00	-1.10	-0.10	1.10	1.00	1.20	1.00
m cd ac	0.78	-0.20	-0.20	-0.20	1.00	-0.10	0.00	1.00	1.00	-1.10	0.00	1.00	1.00	1.10	0.90
m cd ar	0.72	-0.20	-0.20	-0.20	1.00	-0.10	0.00	1.00	1.00	-1.05	0.00	1.00	1.00	1.10	0.90
m cd gr	0.88	-0.20	-0.30	-0.20	1.20	0.00	0.00	1.00	1.00	-1.15	-0.10	1.10	1.10	1.20	0.90
m ww ac	0.97	0.00	-0.20	0.00	1.00	-0.10	0.00	1.00	1.00	-1.00	0.00	1.00	0.90	1.10	1.10
m ww ar	0.90	0.00	-0.20	0.00	1.00	-0.10	0.00	1.00	1.00	-0.95	0.00	1.00	0.90	1.10	1.10
m ww gr	1.07	0.00	-0.30	0.00	1.20	0.00	0.00	1.00	1.00	-1.05	-0.10	1.10	1.00	1.20	1.10
m wd ac	0.80	-0.10	-0.20	0.00	0.80	-0.20	0.00	1.00	1.00	-1.10	0.00	1.00	1.10	1.10	1.00
m wd ar	0.73	-0.10	-0.20	0.00	0.80	-0.20	0.00	1.00	1.00	-1.05	0.00	1.00	1.10	1.10	1.00
m wd gr	0.90	-0.10	-0.30	0.00	1.00	-0.10	0.00	1.00	1.00	-1.15	-0.10	1.10	1.20	1.20	1.00
c cw ac	0.87	0.00	-0.20	-0.20	1.10	0.10	0.00	1.10	1.10	-0.95	0.00	1.00	0.80	1.10	1.10
c cw ar	0.80	0.00	-0.20	-0.20	1.10	0.10	0.00	1.10	1.10	-0.90	0.00	1.00	0.80	1.10	1.10

c cw gr	0.97	0.00	-0.30	-0.20	1.30	0.20	0.00	1.10	1.10	-1.00	-0.10	1.10	0.90	1.20	1.10
c cd ac	0.78	-0.10	-0.20	-0.20	1.10	0.00	0.00	1.10	1.10	-1.00	0.00	1.00	0.90	1.10	1.00
c cd ar	0.72	-0.10	-0.20	-0.20	1.10	0.00	0.00	1.10	1.10	-0.95	0.00	1.00	0.90	1.10	1.00
c cd gr	0.88	-0.10	-0.30	-0.20	1.30	0.10	0.00	1.10	1.10	-1.05	-0.10	1.10	1.00	1.20	1.00
c ww ac	0.97	0.10	-0.20	0.00	1.10	0.00	0.00	1.10	1.10	-0.90	0.00	1.00	0.80	1.10	1.20
c ww ar	0.90	0.10	-0.20	0.00	1.10	0.00	0.00	1.10	1.10	-0.85	0.00	1.00	0.80	1.10	1.20
c ww gr	1.07	0.10	-0.30	0.00	1.30	0.10	0.00	1.10	1.10	-0.95	-0.10	1.10	0.90	1.20	1.20
cwd ac	0.80	0.00	-0.20	0.00	0.90	-0.10	0.00	1.10	1.10	-1.00	0.00	1.00	1.00	1.10	1.10
c wd ar	0.73	0.00	-0.20	0.00	0.90	-0.10	0.00	1.10	1.10	-0.95	0.00	1.00	1.00	1.10	1.10
c wd gr	0.90	0.00	-0.30	0.00	1.10	0.00	0.00	1.10	1.10	-1.05	-0.10	1.10	1.10	1.20	1.10

High N organic matter	Positive biology	Fewer slugs	Fewer weeds	Less disease	SOM	N	P	K	CEC	Nutrient use	Less herbicide	Water Infiltration	Trafficability	Soil Structure	Yield
s cw ac	0.48	-0.10	-0.20	-0.20	0.90	-0.10	0.90	-0.10	-0.10	-1.05	0.00	0.10	0.00	-0.10	0.90
s cw ar	0.42	-0.10	-0.20	-0.20	0.90	-0.10	0.90	-0.10	-0.10	-1.00	0.00	0.10	0.00	-0.10	0.90
s cw gr	0.58	-0.10	-0.30	-0.20	1.10	0.00	0.90	-0.10	-0.10	-1.10	-0.10	0.20	0.10	0.00	0.90
s cd ac	0.40	-0.20	-0.20	-0.20	0.90	-0.20	0.90	-0.10	-0.10	-1.10	0.00	0.10	0.10	-0.10	0.80
s cd ar	0.33	-0.20	-0.20	-0.20	0.90	-0.20	0.90	-0.10	-0.10	-1.05	0.00	0.10	0.10	-0.10	0.80
s cd gr	0.50	-0.20	-0.30	-0.20	1.10	-0.10	0.90	-0.10	-0.10	-1.15	-0.10	0.20	0.20	0.00	0.80
s ww ac	0.58	0.00	-0.20	0.00	0.90	-0.20	0.90	-0.10	-0.10	-1.00	0.00	0.10	0.00	-0.10	1.00
s ww ar	0.52	0.00	-0.20	0.00	0.90	-0.20	0.90	-0.10	-0.10	-0.95	0.00	0.10	0.00	-0.10	1.00
s ww gr	0.68	0.00	-0.30	0.00	1.10	-0.10	0.90	-0.10	-0.10	-1.05	-0.10	0.20	0.10	0.00	1.00
s wd ac	0.42	-0.10	-0.20	0.00	0.70	-0.30	0.90	-0.10	-0.10	-1.10	0.00	0.10	0.20	-0.10	0.90
s wd ar	0.35	-0.10	-0.20	0.00	0.70	-0.30	0.90	-0.10	-0.10	-1.05	0.00	0.10	0.20	-0.10	0.90
s wd gr	0.52	-0.10	-0.30	0.00	0.90	-0.20	0.90	-0.10	-0.10	-1.15	-0.10	0.20	0.30	0.00	0.90
m cw ac	0.53	-0.10	-0.20	-0.20	1.00	0.00	1.00	0.00	0.00	-1.05	0.00	0.00	-0.10	0.10	1.00
m cw ar	0.47	-0.10	-0.20	-0.20	1.00	0.00	1.00	0.00	0.00	-1.00	0.00	0.00	-0.10	0.10	1.00
m cw gr	0.63	-0.10	-0.30	-0.20	1.20	0.10	1.00	0.00	0.00	-1.10	-0.10	0.10	0.00	0.20	1.00
m cd ac	0.45	-0.20	-0.20	-0.20	1.00	-0.10	1.00	0.00	0.00	-1.10	0.00	0.00	0.00	0.10	0.90
m cd ar	0.38	-0.20	-0.20	-0.20	1.00	-0.10	1.00	0.00	0.00	-1.05	0.00	0.00	0.00	0.10	0.90
m cd gr	0.55	-0.20	-0.30	-0.20	1.20	0.00	1.00	0.00	0.00	-1.15	-0.10	0.10	0.10	0.20	0.90
m ww ac	0.63	0.00	-0.20	0.00	1.00	-0.10	1.00	0.00	0.00	-1.00	0.00	0.00	-0.10	0.10	1.10
m ww ar	0.57	0.00	-0.20	0.00	1.00	-0.10	1.00	0.00	0.00	-0.95	0.00	0.00	-0.10	0.10	1.10
m ww gr	0.73	0.00	-0.30	0.00	1.20	0.00	1.00	0.00	0.00	-1.05	-0.10	0.10	0.00	0.20	1.10
m wd ac	0.47	-0.10	-0.20	0.00	0.80	-0.20	1.00	0.00	0.00	-1.10	0.00	0.00	0.10	0.10	1.00
m wd ar	0.40	-0.10	-0.20	0.00	0.80	-0.20	1.00	0.00	0.00	-1.05	0.00	0.00	0.10	0.10	1.00
m wd gr	0.57	-0.10	-0.30	0.00	1.00	-0.10	1.00	0.00	0.00	-1.15	-0.10	0.10	0.20	0.20	1.00
c cw ac	0.53	0.00	-0.20	-0.20	1.10	0.10	1.00	0.10	0.10	-0.95	0.00	0.00	-0.20	0.10	1.10

c cw ar	0.47	0.00	-0.20	-0.20	1.10	0.10	1.00	0.10	0.10	-0.90	0.00	0.00	-0.20	0.10	1.10
c cw gr	0.63	0.00	-0.30	-0.20	1.30	0.20	1.00	0.10	0.10	-1.00	-0.10	0.10	-0.10	0.20	1.10
c cd ac	0.45	-0.10	-0.20	-0.20	1.10	0.00	1.00	0.10	0.10	-1.00	0.00	0.00	-0.10	0.10	1.00
c cd ar	0.38	-0.10	-0.20	-0.20	1.10	0.00	1.00	0.10	0.10	-0.95	0.00	0.00	-0.10	0.10	1.00
c cd gr	0.55	-0.10	-0.30	-0.20	1.30	0.10	1.00	0.10	0.10	-1.05	-0.10	0.10	0.00	0.20	1.00
c ww ac	0.63	0.10	-0.20	0.00	1.10	0.00	1.00	0.10	0.10	-0.90	0.00	0.00	-0.20	0.10	1.20
c ww ar	0.57	0.10	-0.20	0.00	1.10	0.00	1.00	0.10	0.10	-0.85	0.00	0.00	-0.20	0.10	1.20
c ww gr	0.73	0.10	-0.30	0.00	1.30	0.10	1.00	0.10	0.10	-0.95	-0.10	0.10	-0.10	0.20	1.20
cwd ac	0.47	0.00	-0.20	0.00	0.90	-0.10	1.00	0.10	0.10	-1.00	0.00	0.00	0.00	0.10	1.10
c wd ar	0.40	0.00	-0.20	0.00	0.90	-0.10	1.00	0.10	0.10	-0.95	0.00	0.00	0.00	0.10	1.10
c wd gr	0.57	0.00	-0.30	0.00	1.10	0.00	1.00	0.10	0.10	-1.05	-0.10	0.10	0.10	0.20	1.10

Cover Crop	Positive biology	Fewer slugs	Fewer weeds	Less disease	SOM	N	P	K	CEC	Nutrient use	Less herbicide	Water Infiltration	Trafficability	Soil Structure	Yield
s cw ac	0.98	-0.10	0.80	-0.20	0.90	0.90	-0.10	-0.10	-0.10	0.45	0.00	0.10	0.00	-0.10	-0.10
s cw ar	0.92	-0.10	0.80	-0.20	0.90	0.90	-0.10	-0.10	-0.10	0.50	0.00	0.10	0.00	-0.10	-0.10
s cw gr	1.08	-0.10	0.70	-0.20	1.10	1.00	-0.10	-0.10	-0.10	0.40	-0.10	0.20	0.10	0.00	-0.10
s cd ac	0.90	-0.20	0.80	-0.20	0.90	0.80	-0.10	-0.10	-0.10	0.40	0.00	0.10	0.10	-0.10	-0.20
s cd ar	0.83	-0.20	0.80	-0.20	0.90	0.80	-0.10	-0.10	-0.10	0.45	0.00	0.10	0.10	-0.10	-0.20
s cd gr	1.00	-0.20	0.70	-0.20	1.10	0.90	-0.10	-0.10	-0.10	0.35	-0.10	0.20	0.20	0.00	-0.20
s ww ac	1.08	0.00	0.80	0.00	0.90	0.80	-0.10	-0.10	-0.10	0.50	0.00	0.10	0.00	-0.10	0.00
s ww ar	1.02	0.00	0.80	0.00	0.90	0.80	-0.10	-0.10	-0.10	0.55	0.00	0.10	0.00	-0.10	0.00
s ww gr	1.18	0.00	0.70	0.00	1.10	0.90	-0.10	-0.10	-0.10	0.45	-0.10	0.20	0.10	0.00	0.00
s wd ac	0.92	-0.10	0.80	0.00	0.70	0.70	-0.10	-0.10	-0.10	0.40	0.00	0.10	0.20	-0.10	-0.10
s wd ar	0.85	-0.10	0.80	0.00	0.70	0.70	-0.10	-0.10	-0.10	0.45	0.00	0.10	0.20	-0.10	-0.10
s wd gr	1.02	-0.10	0.70	0.00	0.90	0.80	-0.10	-0.10	-0.10	0.35	-0.10	0.20	0.30	0.00	-0.10
m cw ac	1.03	-0.10	0.80	-0.20	1.00	1.00	0.00	0.00	0.00	0.45	0.00	0.00	-0.10	0.10	0.00
m cw ar	0.97	-0.10	0.80	-0.20	1.00	1.00	0.00	0.00	0.00	0.50	0.00	0.00	-0.10	0.10	0.00
m cw gr	1.13	-0.10	0.70	-0.20	1.20	1.10	0.00	0.00	0.00	0.40	-0.10	0.10	0.00	0.20	0.00
m cd ac	0.95	-0.20	0.80	-0.20	1.00	0.90	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.10	-0.10
m cd ar	0.88	-0.20	0.80	-0.20	1.00	0.90	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.10	-0.10
m cd gr	1.05	-0.20	0.70	-0.20	1.20	1.00	0.00	0.00	0.00	0.35	-0.10	0.10	0.10	0.20	-0.10
m ww ac	1.13	0.00	0.80	0.00	1.00	0.90	0.00	0.00	0.00	0.50	0.00	0.00	-0.10	0.10	0.10
m ww ar	1.07	0.00	0.80	0.00	1.00	0.90	0.00	0.00	0.00	0.55	0.00	0.00	-0.10	0.10	0.10
m ww gr	1.23	0.00	0.70	0.00	1.20	1.00	0.00	0.00	0.00	0.45	-0.10	0.10	0.00	0.20	0.10
m wd ac	0.97	-0.10	0.80	0.00	0.80	0.80	0.00	0.00	0.00	0.40	0.00	0.00	0.10	0.10	0.00
m wd ar	0.90	-0.10	0.80	0.00	0.80	0.80	0.00	0.00	0.00	0.45	0.00	0.00	0.10	0.10	0.00
m wd gr	1.07	-0.10	0.70	0.00	1.00	0.90	0.00	0.00	0.00	0.35	-0.10	0.10	0.20	0.20	0.00
c cw ac	1.03	0.00	0.80	-0.20	1.10	1.10	0.00	0.10	0.10	0.55	0.00	0.00	-0.20	0.10	0.10
c cw ar	0.97	0.00	0.80	-0.20	1.10	1.10	0.00	0.10	0.10	0.60	0.00	0.00	-0.20	0.10	0.10

c cw gr	1.13	0.00	0.70	-0.20	1.30	1.20	0.00	0.10	0.10	0.50	-0.10	0.10	-0.10	0.20	0.10
c cd ac	0.95	-0.10	0.80	-0.20	1.10	1.00	0.00	0.10	0.10	0.50	0.00	0.00	-0.10	0.10	0.00
c cd ar	0.88	-0.10	0.80	-0.20	1.10	1.00	0.00	0.10	0.10	0.55	0.00	0.00	-0.10	0.10	0.00
c cd gr	1.05	-0.10	0.70	-0.20	1.30	1.10	0.00	0.10	0.10	0.45	-0.10	0.10	0.00	0.20	0.00
c ww ac	1.13	0.10	0.80	0.00	1.10	1.00	0.00	0.10	0.10	0.60	0.00	0.00	-0.20	0.10	0.20
c ww ar	1.07	0.10	0.80	0.00	1.10	1.00	0.00	0.10	0.10	0.65	0.00	0.00	-0.20	0.10	0.20
c ww gr	1.23	0.10	0.70	0.00	1.30	1.10	0.00	0.10	0.10	0.55	-0.10	0.10	-0.10	0.20	0.20
cwd ac	0.97	0.00	0.80	0.00	0.90	0.90	0.00	0.10	0.10	0.50	0.00	0.00	0.00	0.10	0.10
c wd ar	0.90	0.00	0.80	0.00	0.90	0.90	0.00	0.10	0.10	0.55	0.00	0.00	0.00	0.10	0.10
c wd gr	1.07	0.00	0.70	0.00	1.10	1.00	0.00	0.10	0.10	0.45	-0.10	0.10	0.10	0.20	0.10

Reduced tillage (75% of no-till)	Positive biology	Fewer slugs	Fewer weeds	Less disease	SOM	N	P	K	CEC	Nutrient use	Less herbicide	Water Infiltration	Trafficability	Soil Structure	Yield
s cw ac	0.74	-0.83	-0.90	-0.90	0.68	-0.08	-0.08	-0.08	-0.08	0.34	-0.75	-0.68	0.75	0.68	-0.83
s cw ar	0.69	-0.83	-0.90	-0.90	0.68	-0.08	-0.08	-0.08	-0.08	0.38	-0.75	-0.68	0.75	0.68	-0.83
s cw gr	0.81	-0.83	-0.98	-0.90	0.83	0.00	-0.08	-0.08	-0.08	0.30	-0.83	-0.60	0.83	0.75	-0.83
s cd ac	0.68	-0.90	-0.90	-0.90	0.68	-0.15	-0.08	-0.08	-0.08	0.30	-0.75	-0.68	0.83	0.68	-0.90
s cd ar	0.63	-0.90	-0.90	-0.90	0.68	-0.15	-0.08	-0.08	-0.08	0.34	-0.75	-0.68	0.83	0.68	-0.90
s cd gr	0.75	-0.90	-0.98	-0.90	0.83	-0.08	-0.08	-0.08	-0.08	0.26	-0.83	-0.60	0.90	0.75	-0.90
s ww ac	0.81	-0.75	-0.90	-0.75	0.68	-0.15	-0.08	-0.08	-0.08	0.38	-0.75	-0.68	0.75	0.68	-0.75
s ww ar	0.76	-0.75	-0.90	-0.75	0.68	-0.15	-0.08	-0.08	-0.08	0.41	-0.75	-0.68	0.75	0.68	-0.75
s ww gr	0.89	-0.75	-0.98	-0.75	0.83	-0.08	-0.08	-0.08	-0.08	0.34	-0.83	-0.60	0.83	0.75	-0.75
s wd ac	0.69	-0.83	-0.90	-0.75	0.53	-0.23	-0.08	-0.08	-0.08	0.30	-0.75	-0.68	0.90	0.68	-0.83
s wd ar	0.64	-0.83	-0.90	-0.75	0.53	-0.23	-0.08	-0.08	-0.08	0.34	-0.75	-0.68	0.90	0.68	-0.83
s wd gr	0.76	-0.83	-0.98	-0.75	0.68	-0.15	-0.08	-0.08	-0.08	0.26	-0.83	-0.60	0.98	0.75	-0.83
m cw ac	0.78	-0.83	-0.90	-0.90	0.75	0.00	0.00	0.00	0.00	0.34	-0.75	-0.75	0.68	0.83	-0.75
m cw ar	0.73	-0.83	-0.90	-0.90	0.75	0.00	0.00	0.00	0.00	0.38	-0.75	-0.75	0.68	0.83	-0.75
m cw gr	0.85	-0.83	-0.98	-0.90	0.90	0.08	0.00	0.00	0.00	0.30	-0.83	-0.68	0.75	0.90	-0.75
m cd ac	0.71	-0.90	-0.90	-0.90	0.75	-0.08	0.00	0.00	0.00	0.30	-0.75	-0.75	0.75	0.83	-0.83
m cd ar	0.66	-0.90	-0.90	-0.90	0.75	-0.08	0.00	0.00	0.00	0.34	-0.75	-0.75	0.75	0.83	-0.83
m cd gr	0.79	-0.90	-0.98	-0.90	0.90	0.00	0.00	0.00	0.00	0.26	-0.83	-0.68	0.83	0.90	-0.83
m ww ac	0.85	-0.75	-0.90	-0.75	0.75	-0.08	0.00	0.00	0.00	0.38	-0.75	-0.75	0.68	0.83	-0.68
m ww ar	0.80	-0.75	-0.90	-0.75	0.75	-0.08	0.00	0.00	0.00	0.41	-0.75	-0.75	0.68	0.83	-0.68
m ww gr	0.93	-0.75	-0.98	-0.75	0.90	0.00	0.00	0.00	0.00	0.34	-0.83	-0.68	0.75	0.90	-0.68
m wd ac	0.73	-0.83	-0.90	-0.75	0.60	-0.15	0.00	0.00	0.00	0.30	-0.75	-0.75	0.83	0.83	-0.75
m wd ar	0.68	-0.83	-0.90	-0.75	0.60	-0.15	0.00	0.00	0.00	0.34	-0.75	-0.75	0.83	0.83	-0.75
m wd gr	0.80	-0.83	-0.98	-0.75	0.75	-0.08	0.00	0.00	0.00	0.26	-0.83	-0.68	0.90	0.90	-0.75

c cw ac	0.78	-0.75	-0.90	-0.90	0.83	0.08	0.00	0.08	0.08	0.41	-0.75	-0.75	0.60	0.83	-0.68
c cw ar	0.73	-0.75	-0.90	-0.90	0.83	0.08	0.00	0.08	0.08	0.45	-0.75	-0.75	0.60	0.83	-0.68
c cw gr	0.85	-0.75	-0.98	-0.90	0.98	0.15	0.00	0.08	0.08	0.38	-0.83	-0.68	0.68	0.90	-0.68
c cd ac	0.71	-0.83	-0.90	-0.90	0.83	0.00	0.00	0.08	0.08	0.38	-0.75	-0.75	0.68	0.83	-0.75
c cd ar	0.66	-0.83	-0.90	-0.90	0.83	0.00	0.00	0.08	0.08	0.41	-0.75	-0.75	0.68	0.83	-0.75
c cd gr	0.79	-0.83	-0.98	-0.90	0.98	0.08	0.00	0.08	0.08	0.34	-0.83	-0.68	0.75	0.90	-0.75
c ww ac	0.85	-0.68	-0.90	-0.75	0.83	0.00	0.00	0.08	0.08	0.45	-0.75	-0.75	0.60	0.83	-0.60
c ww ar	0.80	-0.68	-0.90	-0.75	0.83	0.00	0.00	0.08	0.08	0.49	-0.75	-0.75	0.60	0.83	-0.60
c ww gr	0.93	-0.68	-0.98	-0.75	0.98	0.08	0.00	0.08	0.08	0.41	-0.83	-0.68	0.68	0.90	-0.60
cwd ac	0.73	-0.75	-0.90	-0.75	0.68	-0.08	0.00	0.08	0.08	0.38	-0.75	-0.75	0.75	0.83	-0.68
c wd ar	0.68	-0.75	-0.90	-0.75	0.68	-0.08	0.00	0.08	0.08	0.41	-0.75	-0.75	0.75	0.83	-0.68
c wd gr	0.80	-0.75	-0.98	-0.75	0.83	0.00	0.00	0.08	0.08	0.34	-0.83	-0.68	0.83	0.90	-0.68