High biomass rotation and its impacts on soil health, weed burden and crop production

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Richard Gantlett

Abstract

Communicating the importance and value of the soil has never been more urgent. The soil is a foremost resource supporting human society, facilitating food and fibre production, protecting against drought and flood, cycling nutrients, harbouring functioning biodiversity and storing carbon. Yet soil degradation is one of the greatest threats to our future, as it diminishes these soil functions. This thesis assesses the viability of a sustainable approach to soil regeneration, while maintaining the productive function. A five-year experiment was set up on-farm, in an existing organic and biodynamic crop rotation, to explore the impact of in-situ grown biomass used as edaphic food. A standard treatment included plant necromass and root exudates from a rotation of 2-year diverse (23 species) ley, combinable crops, and green manure all constituted biomass input; an enhanced treatment retained crop residues in addition. Comparisons to a 5-year diverse ley and a fallow were also made. Soil health, weed burden and crop production were monitored to follow the change in, and outcomes of, soil function, over this period.

Soil organic matter increased in the crop rotation whether crop residues were retained or not. The five years diverse ley resulted in a larger increase in soil organic matter, and bulk density and aggregate stability compared to the other treatments. The amount of organic matter in the top 100 mm of soil increased by between 1.21% and 3.14% yr^{-1} in the biomass input treatments and at the 100-300 mm depth by between 0% and 1.57% yr^{-1}. These outcomes easily surpass the COP21 target of 0.4% annual increase in soil organic carbon stock, at the 0-100 mm soil depth with no loss or greater at the 100-300 mm depth.

An increase in biodiversity was found when adding the biomass rather than removing it; soil mesofauna counts increased by 33% with retaining crop residues from combinable crops. These findings demonstrate important ecosystem services that could be provided by adding biomass to the soil. Mesofauna are multifunctional soil organisms, processing leaf litter, consuming pathogenic fungi, supplying nutrients available for plants and playing an important role in the carbon cycle. Weed burden did not change between treatments in crops. Weeds can limit crop production but also provide valuable flowers for insect pollinators, shelter and food for insects, small mammals, and birds, together with root diversity for improved soil root community dynamics. There was no change to yield from retaining crop residues.

This study found that farm ecological performance can be improved by returning crop biomass to the soil, and diverse leys can store globally important quantities of soil carbon, this is both a climate change mitigation and adaptation strategy.

Acknowledgements

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Preface

Richard Gantlett has been farming in Wiltshire at Yatesbury House Farm since January 1992. The land was farmed conventionally with arable crops in rotation and a reducing beef cattle enterprise. The straw burning ban in the 1990s prompted the introduction of the plough as a method of incorporating crop residues into the soil, and in 1998 a conversion to organic farming methods was initiated. Diverse ley mixtures, sometimes referred to as herbal leys, were introduced in 2000 to enhance the fertility building nature of the ley phase of the rotations. Following years of experimenting with organic methods, in 2003 Richard took the unusual step of switching to reduced tillage whilst continuing with organic farming. Field beans in mixtures with other species were also used as annual green manures. Cattle were re-introduced to the farm as a source of income from the fertility building, diverse ley, phase of the rotation.

The setting up and running of the experiment for this doctoral research has had a profound effect on the farm and enhanced the soil regeneration processes that had already been put in place. Given the nature of the farming practices and continuous experimentation, the farm has always felt like a research station without a scientist. This doctoral research hopes to bring scientific rigour to everyday trial and error that happens on every farm in the world.

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Chapter 1. General Introduction

1. Soil Degradation

A picture speaks a thousand words, so a visual indication of the depletion of soil resource in England is perhaps the best place to start (Figure 1.1). Whilst Northern England and Scotland can be seen with snow on the hills and mountains, the rivers from Central and Southern England discharge enormous quantities of brown plumes of soil into the surrounding seas. The difference is not due to the snow cover, but far more likely due to soil discharge from annual cropping that takes place in England. It is the degradation of agricultural soils and the potential of modern crop rotations to reverse this process that is the focus of this thesis.

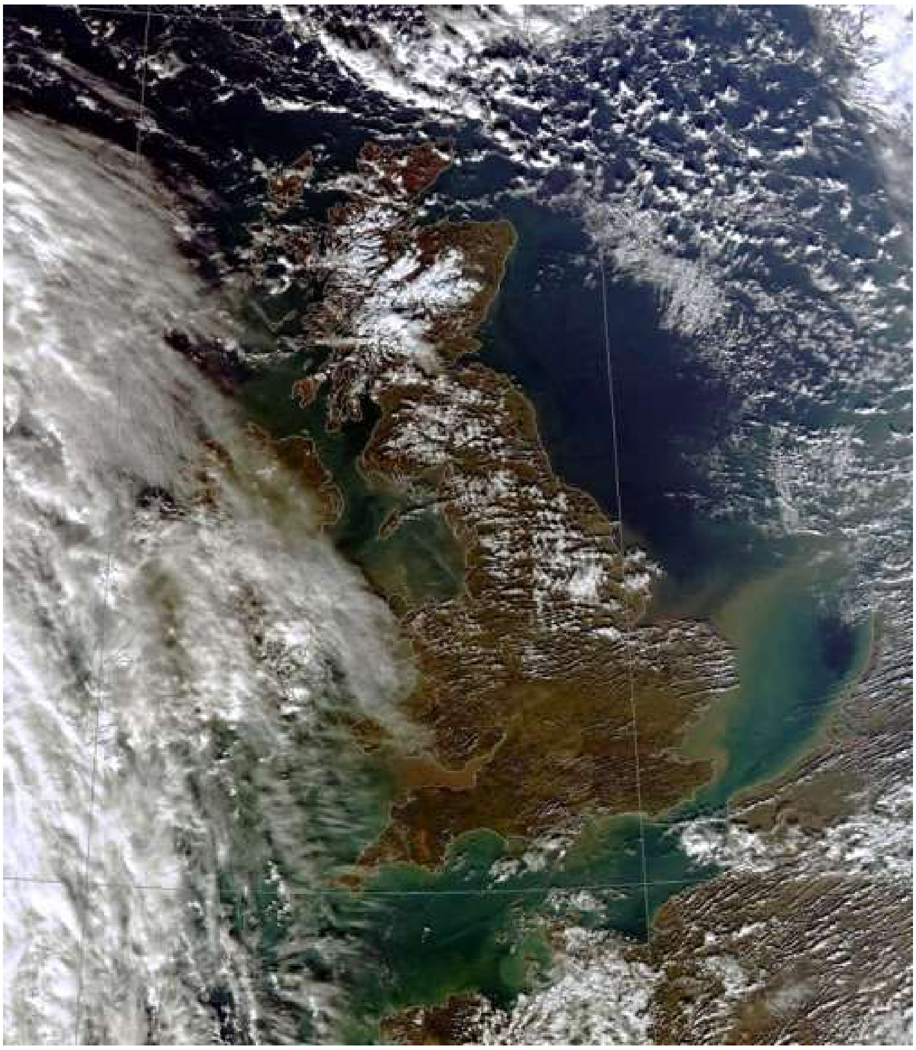
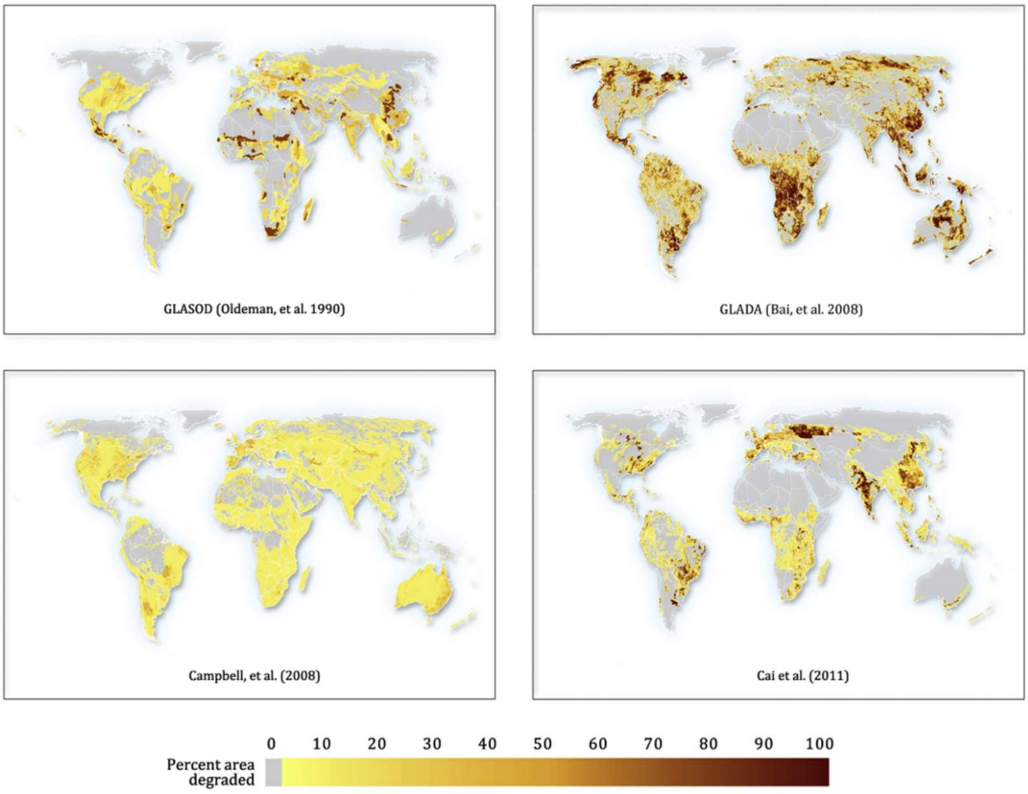


Figure 1.1 Brown plumes of soil seen flowing into the coastal zone (Jones 2016)

Soil degradation is defined as a long-term decline in the soil ecosystem function and productivity (Bai et al. 2008), however following land use change soil degradation can happen quickly via erosion for example (Borrelli et al. 2017). Soil degradation in an agricultural context starts with the removal of the permanent cover of natural flora. This may be a rainforest of South America, prairie or forest of Eastern Europe, temperate woodland or scrub and grasslands in Western Europe and the UK or the bush of outback Australia. Permanent natural ecosystems involve little or no removal of plant material (except through wildfire events), rather the in-situ recycling of biomass or elements. Lal and Stewart (1992) show that the soil stock across the planet is being degraded by a combination of a changing climate, anthropogenic over-exploitation, urbanization and introgression by non-native species. Although the soil has a built-in resilience to the effects of external factors there is a limit to the buffering capacity of the biotic and abiotic components of the soil to change (Lal and Stewart 1992). Gibbs and Salmon (2015) have brought together four mapping projects focused on soil degradation to give a global perspective in Figure 1.2.


GLASOD (Oldeman, et al. 1990)

GLADA (Bai, et al. 2008)

Campbell, et al. (2008)

Cai et al. (2011)

Figure 1.2 Maps of land areas affected by degradation with four different approaches (percent of cell area), all shown with common legend and 20 km grid. (Gibbs and Salmon 2015)

1.1 **Categories of degradation**

The Global Assessment of Human Induced Soil Degradation (GLASOD) (Bridges and Oldeman 1999) focused on four categories of soil degradation shown in Figure 1.3.

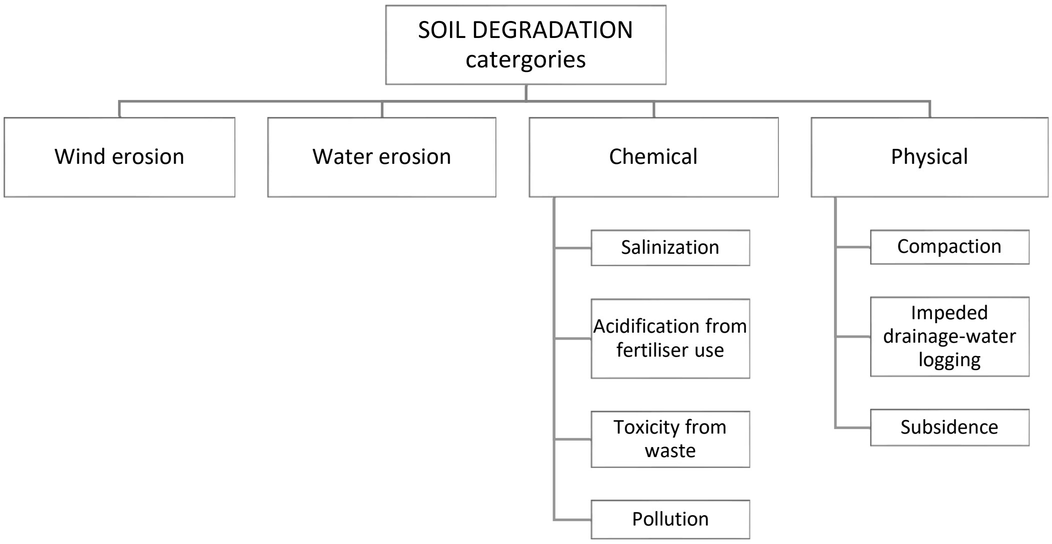


Figure 1.3 Causes of Soil Degradation, adapted from (Lal and Stewart 1992, Bridge and Oldeman 1999)

Soil erosion is a complex process that depends upon soil properties, topography, vegetation, and rainfall amount and intensity (Selby 1993). A soil with a well aerated structure and with high organic matter and permanent vegetation cover will have a high-water infiltration rate and storage capacity. Good soil structure will allow water to infiltrate through, rather than run across the surface, and thus regulate the flow of water at high and low rainfall periods. At high rainfall intensity, poor soils, with no vegetation, result in subterranean aquifers being by-passed in preference for surface runoff to rivers, leading to greater river flows extremes. Indicators of this after high rainfall events are silt plumes in rivers (Figure 1.1), topsoil washed into field gateways or onto highways, and eroded gullies in fields.

Although soil fertility generally declines with accelerating erosion, soil fertility is itself a function of agricultural methods and site conditions such as soil type, nutrient content and organic matter content (Montgomery 2007). Erosion of soil by water occurs after heavy rains where crop cover has been removed to enable short-term cropping. This effect is strongest on sloping land where the ability of the soil to absorb water has been reduced by farming practices. The worse the soil is degraded, the lower the gradient necessary to cause soil erosion.

Wind erosion is a serious global concern (Webb et al. 2020). Borrelli et al. (2017) show that global soil erosion has been greatly underestimated due to current land use change. Figure 1.4 below highlights the effect of different land uses on soil erosion rate.

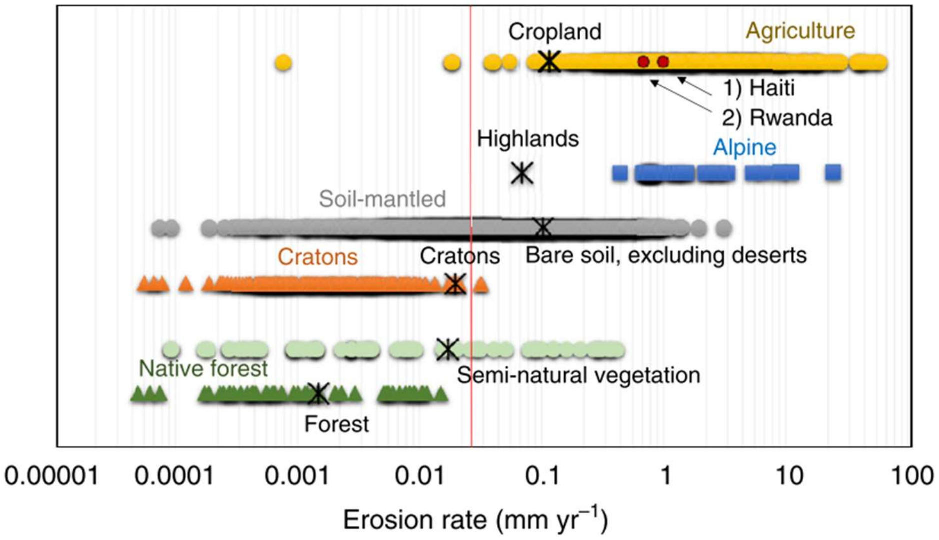


Figure 1.4 Comparison of measured and modelled erosion rates. Representation of soil erosion rates measured on agricultural fields under conventional agriculture (n = 779), geologic erosion rates measured on alpine terrain (n = 44), soil-mantled landscapes (n = 1456), low gradient continental cratons (n = 218), grassland and scrublands (n = 63), native forests (n = 46) and averages of our predictions (indicated by an asterisk). Large parts of the measured data come from the study of Montgomery (2007) integrated with data from other meta-analysis studies. The vertical red line indicates average value of soil erosion. The red dots refer to averages soil erosion rates modelled for two countries (Haiti and Rwanda) highly susceptible to water erosion (Borrelli et al. 2017).

Figure 1.5 Wind erosion of peat soils and impeded drainage Left: near Whitehall Farm, Peterborough, UK, “The Fen Blow” curtesy S. Briggs. Right: compacted soil with manure heaps, Wiltshire, UK.

The photographs in Figure 1.5, show that wind erosion is an important factor in highly organic, dry Fen soils of the UK and impeded drainage can be caused by inappropriate manure handling on a dairy farm in Wiltshire.

1.2 **Causes of Soil Degradation**

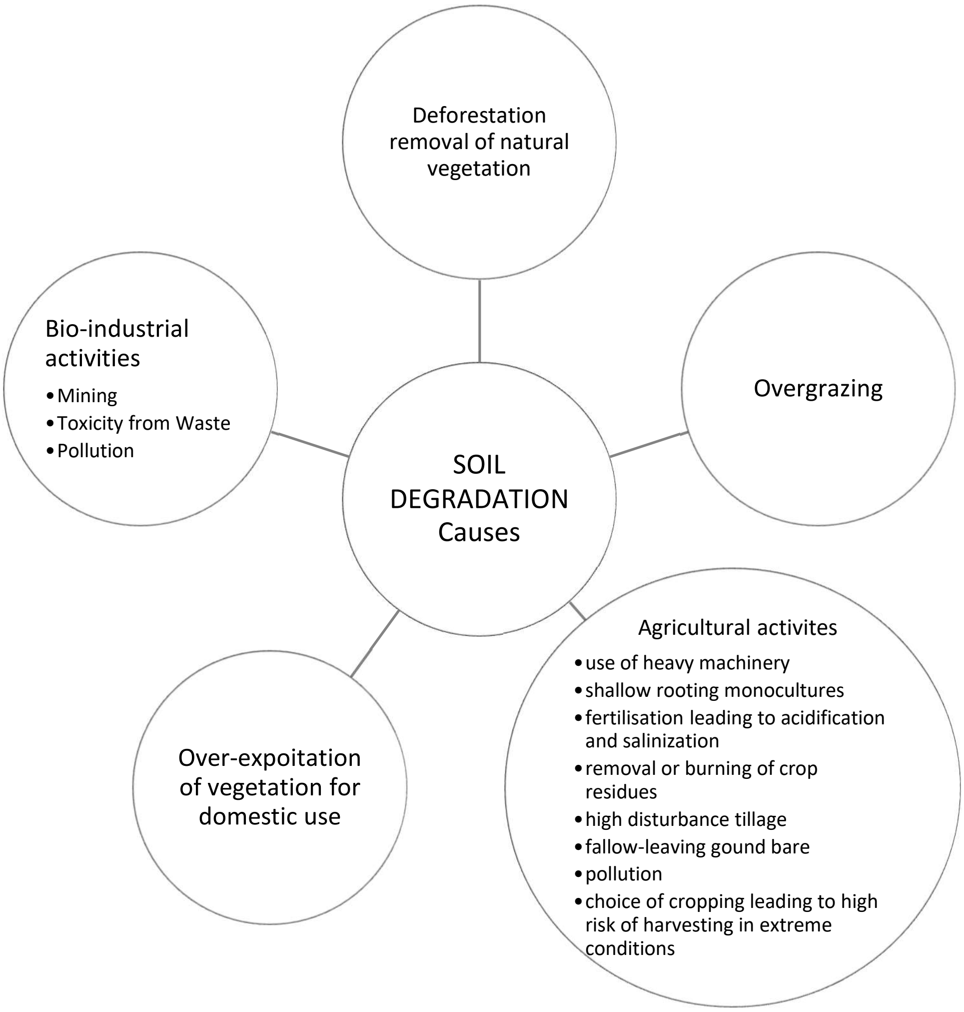


Figure 1.6 Causes of Soil Degradation adapted from (Lal and Stewart 1992, Bridges and Oldeman 1999, Montgomery 2007)

Human induced soil degradation is caused by overexploitation of the soil (Figure 1.6), a situation brought about by poverty, ignorance, and an inability to adopt a sustainable system of agriculture (Bridges and Oldeman 1999). Tilman et al. (2002) specifically describe how soil degradation has been related to intensive cultivation systems based on repeated tillage, heavy application of synthetic fertilizers as well as fumigants and fungicides. Heavy metals and xenobiotics (e.g. microplastics) have also led to soil degradation through pollution (Moolenaar et al. 1997). All these have magnified soil erosion losses and the soil resource base has been steadily degraded. Similar soil degradation can occur on permanent grasslands by overgrazing of stock, often by a process known as set stocking (Bridges and Oldeman 1999). Set stocking is where animals are limited to one area over a long period, the pasture and its regrowth is therefore continually restricted by further immediate grazing, the plants cannot develop to their full potential and so their root systems become restricted. In contrast, occasional/rotational/intense grazing can increase belowground carbon compared to no grazing (Reeder and Schuman 2002). Montgomery's (2007) assessments, partly indicated in the figure below, have produced a stark estimate of global soil degradation through erosion, showing that historical and current agricultural practice is not sustainable as it risks depleting the soil resource within the foreseeable future.

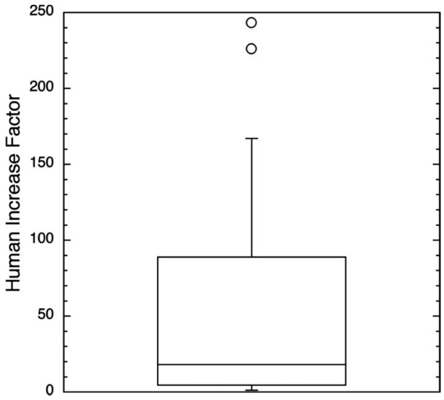


Figure 1.7 Range of reported Increases in erosion rate, boxplot, of studies reporting direct comparisons of erosion under conventional agriculture vs. native vegetation for comparable settings (n=46, median =18, mean =124, minimum =1.3, max 1,878). Data include studies that reported both rates individually and those that simply reported a ratio between erosion rates under native vegetation and conventional cultivation (Montgomery 2007).

1.3 **Impacts of Soil Degradation**

The impacts of soil degradation are broad and felt at all scales, Figure 1.8. The global stock of carbon held in soils is the largest terrestrial store of carbon, around 3 times that held by earth biomass (Bellamy et al. 2005). Scharlemann et al. (2014) calculate the mean (±standard error) of the 11 model results of global carbon stocks was 1520 ± 770 Pg C. Bellamy et al. (2005) estimate the total rate of carbon loss across the UK is 13 Tg/yr. Reduction of soil organic carbon (Loveland and Webb 2003) has contributed to greenhouse gas emissions and climate change and loss of natural soil suppression of plant pathogens (Weller et al. 2002). Soil microbial diversity and its taxonomic composition are profoundly affected by cultivation management practices such as tillage regime (Shi et al. 2013), fertilization (Fierer et al. 2012), and pest management (Wei et al. 2016).

Soil biodiversity loss will naturally lead to above ground biodiversity loss in plants (Wagg et al. 2014). The loss in insect numbers has recently been recorded in Germany (Hallmann et al. 2017) and has also been noted by anyone driving a car between the 1990s and today, in what is known as the windscreen effect. Gilroy et al. (2008) found a causal link between soil compaction and the insect eating yellow wagtail decline and they suspect that the role of soil degradation in farmland bird decline has been overlooked. Bonanomi et al. (2016) note that in the last decades soil degradation has caused salinization leading to a reduction in crop productivity worldwide (Sumner 1995). Grassini et al. (2013) reports plateaus in some of the world's major cereal producing areas, despite no link to soil degradation being suggested, the scale of soil degradation is likely to be a cause but evidence is divergent and unverified (Bindraban et al. 2012).

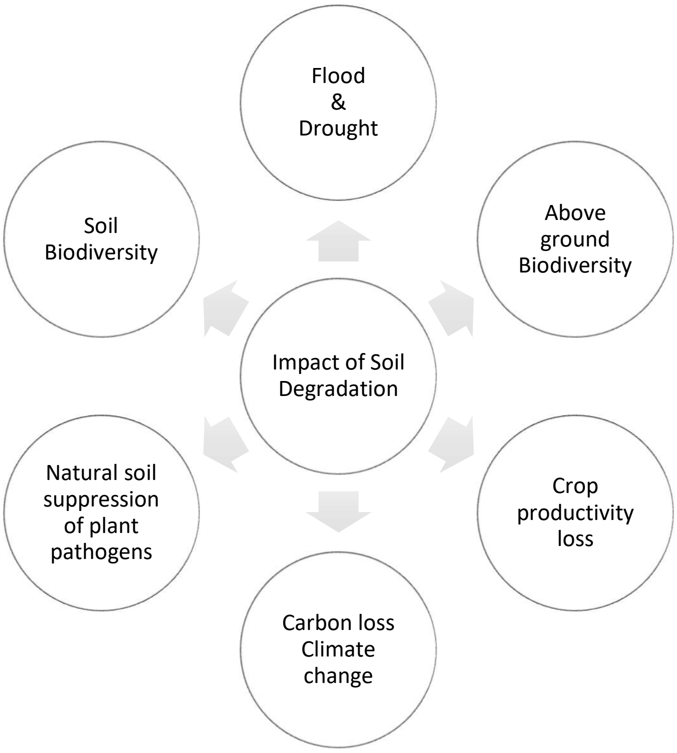


Figure 1.8 Impact of soil degradation, adapted from (Sumner 1995, Tilman et al. 2002, Weller et al. 2002, Loveland and Webb 2003).

Through the understanding of the capacity of soils to manage water and nutrients, soil degradation will lead to greater drought and flooding vulnerability (Falkenmark and Rockström 2008). In the desertification prone savannas of Sub-Saharan Africa Falkenmark and Rockström (2008) found that "drylands are in fact not that dry after all". With no recent change to meteorological rainfall, low crop yields may have been due to dry spells rather than drought as soils have been degraded and managed so as to lose their ability to supply plants with moisture during dry spells.

1.4 **Climate Change and Soil Degradation**

Climate change will exacerbate any current flood or drought risk described above (Weisheimer and Palmer 2005, Beniston et al. 2007, Falkenmark and Rockström 2008). Figure 1.9 shows the climate change impact on European critical regions, where what are 100-year flood and drought events today may recur every 10–50 years by the 2070s (Lehner et al. 2006).

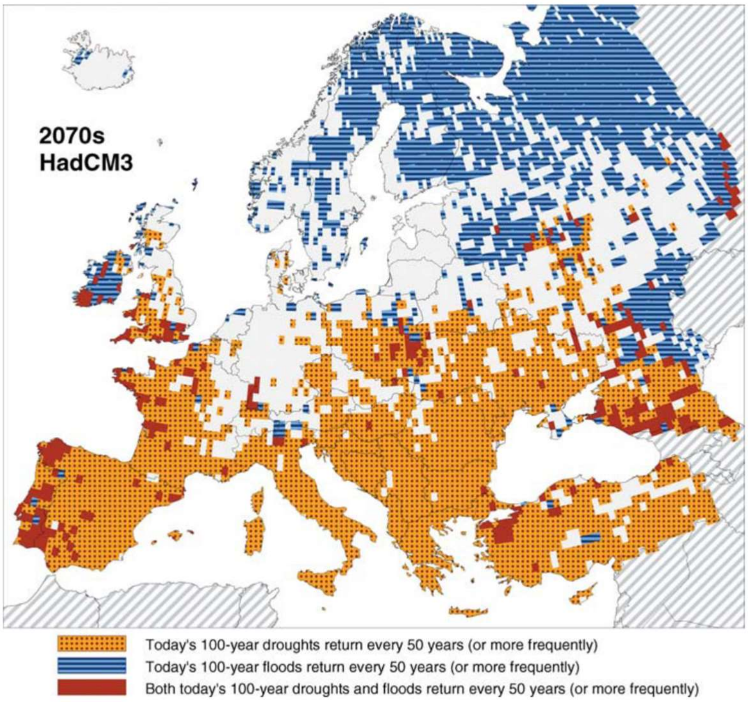


Figure 1.9 Critical regions of flood and drought as referred to (i) a decrease in the return period of the current 100-year drought to 50 years or less and (ii) a decrease in the return period of the current 100-year flood to 50 years or less. Values calculated with WaterGAP 2.1, based on HadCM3 climate model and Baseline-A water use scenario for the 2070s (Lehner et al. 2006).

Climate change has a greater potential to cause high impact, non-linear, climate tipping points. The potential collapse of the Atlantic Meridional Overturning Circulation (AMOC) is such as tipping point and would lead to land use change in the UK with severe loss of arable areas in the East of England (Ritchie et al. 2020). The capacity of the soil to buffer these events will become increasingly important and therefore the need to reverse the direction of soil development is all the more apparent. Soils can provide both climate adaptation by storing water (Falkenmark and Rockström 2008) and climate change mitigation option by sequestering carbon (Paustian et al. 1997, Paustian et al. 2016, Amundson and Biardeau 2018, Lal et al. 2018). Understanding the nature of the soil needs to be the first step in halting the decline in the global soil resource.

2. Describing and defining soil

Soil is a multi-faceted resource which has been used for agriculture for many thousands of years. In defining a soil in the agricultural context, natural limiting factors affect the development of that soil: geology, topography, biota, climate and time depicted in Figure 1.10.

2.1 **Soil creation and development**

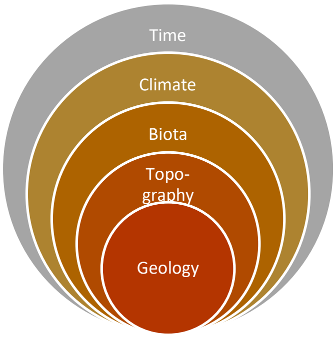


Figure 1.10 Major soil forming factors (Jenny 1946)

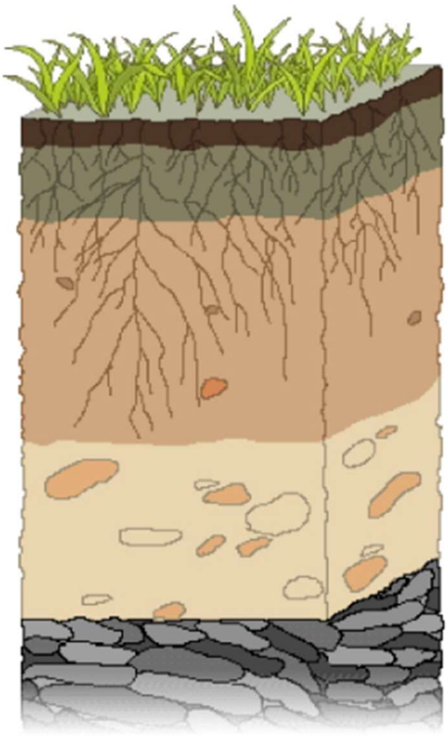
Geology is the mother rock formation on which the soil is founded and starts to develop. In practical terms, the geology is fixed. As the soil grows and matures, non-geological factors gain greater influence on its capacity to function.

Soil climate is the single most important factor in categorising soils (Bockheim et al. 2014). Climate such as rainfall, hours of sunshine, wind, salt deposition (sea spray) and temperature are specific to each location on Earth and vary greatly over time. Together these soil forming factors determine the rates of chemical, physical and biological processes in the soil and therefore exert a strong influence on soil development. Human interventions such as irrigation or protected cropping are able, at various scales, to modify the climate thereby extending the possibilities of cropping. However, these interventions have their own impact on soil quality, generally accelerating soil processes (whether they are negative or positive) (Murray and Grant 2007, Trost et al. 2013, Mudge 2017).

Biota in the soil are the fauna and flora. "…Everything is everywhere but the environment selects…" is a well know maxim by Baas Becking (1934) as cited in (De Wit and Bouvier 2006). This idea describes that microbial life is everywhere in its full diversity, but different communities of microbes exist in different environments because the pervading conditions select those organisms which are best adapted for a given set of conditions. It is the small creatures which at first develop rock into soil by helping to reduce particle size and adding organic matter another key soil constituent. However, the notion of everything everywhere has being challenged by the observation of invasive species which change from being minor components of their native communities to dominant components of invaded communities (Callaway and Maron 2006). Earthworms and fungi are two of the well-known biota species and well known for aggregating soil particles (Six and Paustian 2014). Soil fauna generally form an important feedback loop between plants and soil especially in terms of plant litter decomposition (Frouz 2018).

Topography is a major determinant in the movement of soil resources from one location to another. Gravity and water flow will transport fine rock particles and chemicals dissolved in soil solution, thus leading to soil horizon development. Topography interacts with climate to modify wind, rain, light and temperature effects on the soil. It facilitates breaking of rock into smaller particles through erosion and fluvial action, it modifies growth of all living organisms within the soil through shade or temperature.

Time's influence on soil is apparent in the soil's development. The less time a soil has had to develop, perhaps due to changing water/ice levels or geological changes, then the smaller the soil horizons shown in the Figure 1.11 will be. Indeed some horizons particularly the organic and substratum may be missing in young soils (Sheffield 2017).



O (Organic): ~50 mm deep; made up of dead plant material: leaves and twigs

A (Surface): This upper horizon is also called Topsoil. It is 100-250 mm deep and consists of organic matter and minerals. This is the soil layer where plants and soil organisms primarily live.

B(Subsoil): This layer is mostly made of clay, iron mineral as well as organic matter, which has been washed down by rainwater.

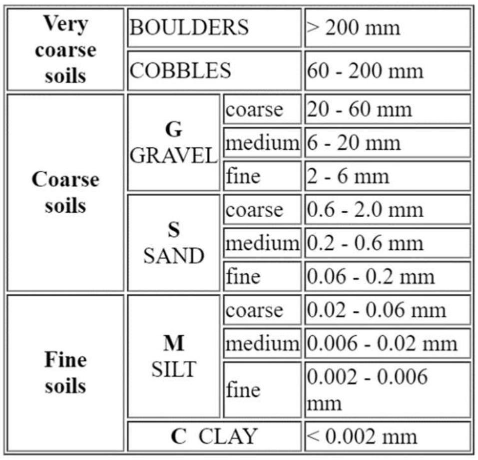
C(Substratum): The C horizon is the parent material from which the upper soil layers developed. It consists primarily of large rocks

R(Bedrock): This is the bedrock and is located several feet under the surface. It is a solid mass of rock

Figure 1.11 Soil horizons (Sheffield 2017))

2.2 **Soil classification, texture and components**

Different countries tend to have their own system of classification which has either developed separately or adapted from other systems to suit their own circumstances (FAO 2020). The system may also vary depending on the use of the soil, such as agriculture or construction. Soils vary widely depending upon their natural resources as described above, to an almost limitless extent. Soil classification places similar soils into groups so they can be compared, cross referenced and viewed by agriculturalists, salesmen and researchers into what are functional groups, whether it be demonstrating suitability for growing different crops or suitability for other uses. In the UK an Agricultural Land Classification system was set up to put land into 7 grades, grades 1 to 5 with grade 3 being in 3 parts, depending upon value and use for agricultural purposes (MAFF 1988). Alternatively, the Soil Classification System for England and Wales shows geographic soil associations identified by the most frequently occurring soil series relating to soil profiles or horizons (LandIS 2017). Soil textural class is another system of classification which uses mineral particle size to differentiate soils, Figure 1.12 shows how soil particle size translates to sand, silt and clay, commonly referred to as texture. The soil texture (of the soil minerals) is a fixed component of the soil, which is not changed through farming practice nor short-term climate and does not consider soil organic matter. However, the clay and fine silt content are important in soil organic matter accumulation and soil aggregation. The USDA and UK versions of the soil textural triangle used to define textual classes are amalgamated in Figure 1.13. and are widely recognised, with the soil textural groups being commonly referred to by land managers.



Very coarse soils	BOULDERS		> 200 mm
	COBBLES		60 - 200 mm
Coarse soils	**G** GRAVEL	coarse	20 - 60 mm
		medium	6 - 20 mm
		fine	2 - 6 mm
	S SAND	coarse	0.6 - 2.0 mm
		medium	0.2 - 0.6 mm
		fine	0.06 - 0.2 mm
Fine soils	**M** SILT	coarse	0.02 - 0.06 mm
		medium	0.006 - 0.02 mm
		fine	0.002 - 0.006 mm
	C CLAY		< 0.002 mm

Figure 1.12 Soil basic particle size groups (UWE 2017)

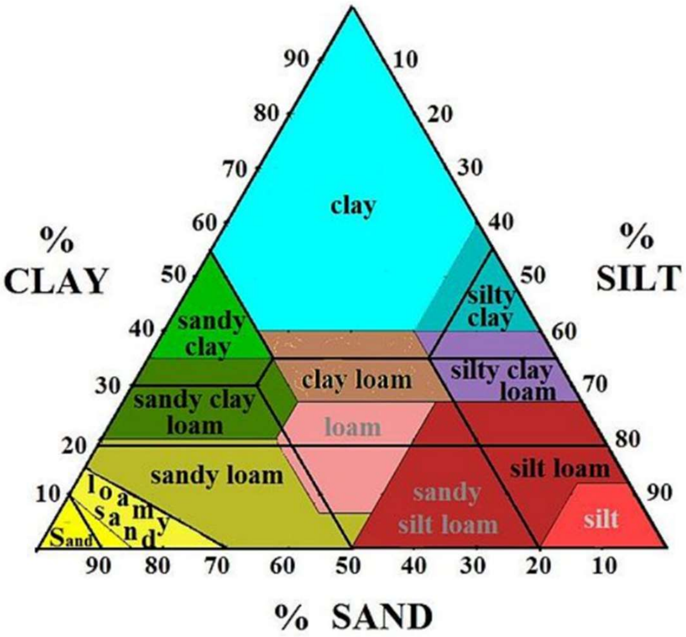


Figure 1.13 Soil textural triangle showing both the USDA (colours) and the UK-ADAS (black lines), soil classes (McEwen 2012)

They are important in this context because of the greater ability of the clay and fine silt soils to physically protect soil organic matter by soil particle aggregation described in section 3 of this chapter. Loam is a term used for a mixture of sand, silt and or clay which avoids the extremes. These textural classification systems do not describe either the organic matter in the soil, nor the living community. They provide a base from which to begin describing soils and to begin understanding possible soil processes available in terms of soil improvement given a particular soil texture. It could be said that the more organic matter and life there is in different soils the closer the functional ability of those different soils becomes. A soil is not just made of mineral particles (Figure 1.14), what separates a soil from ground rock is its ability to support life and for most life, air and water are required. It is the presence of organic matter that makes the difference between a collection of soil mineral particles and a functioning soil with recognisable physical structure (Powlson et al. 2013). Another requirement for life is food, organic matter is the soil life's food store. Figure 1.14 shows the relative proportions by volume of these ingredients in a soil in good condition, highlighting the soil pore space which is available for organisms such as plants and earthworms to occupy.

Compacted soils would give a dramatically different picture where much of the air and water are removed depending upon the degree of compaction, leading to less space for biota to exist in and therefore leading to degradation of the soil (Chaparro et al. 2012). This is explored below.

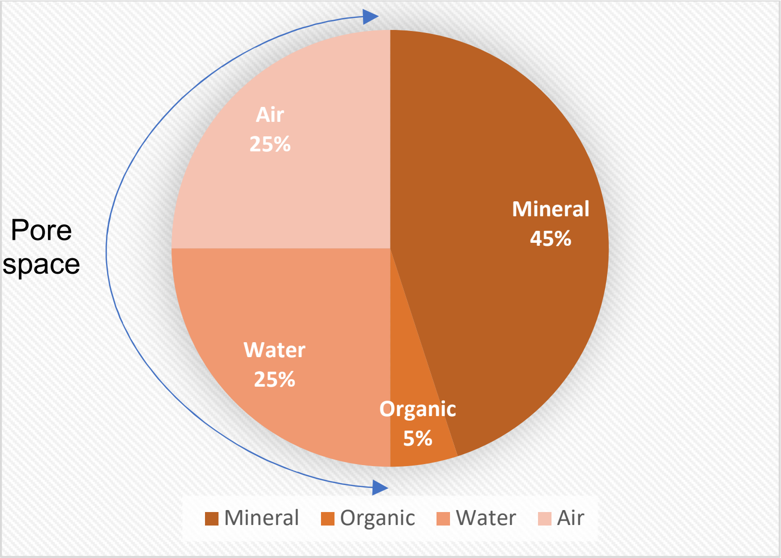


Figure 1.14 Soil components by volume in a soil of good state (Brady and Weil 1999)

2.3 **Chernozem soils -Nature's good example**

Chernozem soils are rich black soils found mostly in Russia, Ukraine, Northern Kazakhstan, the great plains of the USA and Canada, forming part of the Mollisols soil classification in the US, Figure 1.15. Formed from historic permanent grassland areas known as Steppes these soils are particularly fertile with high organic matter levels. The name of the soil, "cherniy" meaning black, attests to the high carbon content of the soil and "zem" meaning earth.

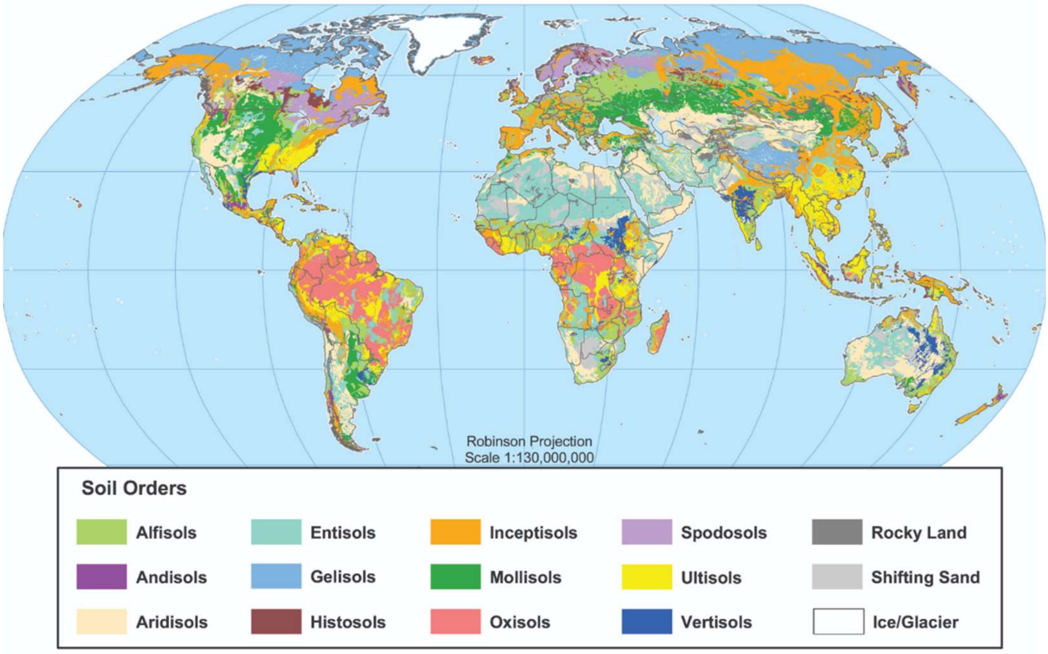


Figure 1.15 Global soil regions, Chernozem shown here in Mollisols (USDA 2005), Mollisols (Chernozems, Kastanozems, Phaeozems) are characterized by a dark, high SOM, A horizon.

Deposition and retention of plant material belowground in the grassland system has been the primary factor whereby soil organic matter accumulates within Chernozem soils (Fuller 2010) in a process called melanisation (Chesworth 2008). Chernozems are typical for their high potential fertility maintained by their great reserves of organic matter and nutrients, neutral or weakly acid reaction, and favourable soil structure and water regime (Nosko 2013), Figure 1.16.

Figure 1.16 Figure 1.16 The profiles of virgin Chernozem soils Central Russian Upland: 1-Streletskaya Steppe; 2-Yamskaya Steppe; 3-Kamennaya Steppe (Chendev et al. 2015).

The soil at Yatesbury House Farm, the experimental site in this thesis, became prone to draught and flooding following a decline in the use of leys, grazing animals and an intensification of tillage and the use of agrochemicals and fertilisers. The goal at Yatesbury is to create a soil akin to a Chernozem from its Blewbury and Yatesbury series soils. Blewbury series is a well-drained, calcareous, clayey, over argillaceous chalk with Yatesbury series being fine silty over clayey over argillaceous chalk (Findlay and Colborne 1984). The soils were first recorded in the 1970s with 1.7-2.1% organic carbon in the top 22cm (Findlay and Colborne 1984).The temperate UK climate is one of the limiting factors in creating a Chernozem soil, as a freezing Winter is typical in Chernozem regions. The freezing provides natural fracturing of the soil profile enabling infiltration of thawing water followed by air in the spring. Two vital components of soil life therefore being readily available (air and water). Rainfall in the Steppe region of Ukraine, where Chernozem is abundant, is currently 250-550mm per annum, which is half that expected at Yatesbury. The other ingredient to soil formation is organic matter which was originally provided by the prairie grass (or in some areas mixed grass-forest). This was indigenous in these areas of Steppe land in Ukraine, Russia, USA and Canada where the Chernozem soils exist naturally today.

3. Soil Organic Matter

Soil organic matter (SOM) includes decomposing plant and animal material in the soil. SOM facilitates many of the soil functions which will be described below (Loveland and Webb 2003). It provides food for many of the soil biota (Kramer et al. 2012). It comprises a whole range of simple and complex organic compounds. Some organic compounds are eaten or decomposed more readily than others.

3.1 **Soil food**

Cellulose, the most abundant organic compound (polysaccharide) on earth, is digestible by specially adapted bacteria which inhabit grazing animals with a rumen and crucially by saprophytic fungi (Hammel 1997). More woody material contains lignin (Hammel 1997) the next most abundant poly-carbon (multi-variant phenylpropanoid) (Lu and Ralph 2010), which is harder to decompose, resists water, remains longer in the soil and thought to contribute to a more stable SOM. As the organic compounds transfer along the food chain in the soil, they are broken up and form longer bio-associations with soil minerals producing more stable and more complex molecules. Polyphenols or biophenols are organic molecular groups that are joined together to form biopolymers such as lignin. Specific enzymes are produced by microbes that catalyse a free-radical scission mechanism that break down lignin to smaller compounds (Stevenson and Cole 1999). Polysaccharides in soils are important because they bind soil particles into water stable aggregates, with the result that a soil with a high polysaccharide content is more permeable to water and air than one with low content (Stevenson and Cole 1999). Chitin is another common polysaccharide made by chains of modified glucose, often found in the hard exo-skeletons of insects and arthropods and in the relatively hard tubes of fungal hyphae (Muzzarelli 1977, Muzzarelli et al. 1986, Paterson and Kennedy 1999). It matters therefore what the constituents of the SOM are, as this determines the community of biota that live in the soil (Kramer et al. 2012). It would follow that in order to maintain a wide variety of soil biota a wide variety of food sources are needed.

3.2 **Soil structure**

Organic matter association with soil particles brings about functional soil structure. This association creates a recognisable physical structure, able to support the ingress of air, water and biota and thus becoming a suitable medium for plant growth. Regarding soil structure, glomalin, a glycoprotein produced by the hyphae of Arbuscular Mycorrhizal Fungi (AMF), has received much attention with respect to its suggested role in the stabilisation of microaggregates (Smith and Smith 1997, Driver et al. 2005, Janos et al. 2008, Xie et al. 2015). Polysaccharides have also been found to act as particle glue but only in aggregates less than 50µm diameter (Tisdall and Oades 1982). Other hydrophobic proteins produced by mycorrhizal fungi and filamentous bacteria, such as hydrophobins and chaplins, have also been associated with microaggregate formation and stabilisation (Gougoulias 2014). In exploring the mechanism by which glomalin is released into the soil by AMF Driver et al. (2005) found that glomalin was not easily separated from fungal walls suggesting that glomalin is released by the action of the soil microbial community in degrading decaying hyphae rather than primarily through secretion.

Soil physics is not just about the presence of SOM but indeed the careful arrangement of that SOM by the soil biota. AMF are one example of the many organisms including earthworms (Briones 2014, Six and Paustian 2014), soil invertebrates (Jouquet et al. 2006, Lavelle et al. 2006) and soil macro and mesofauna (Frouz 2018), that organise the soil to build their homes in such a way that gives function to the soil for other plants and animals, enabling agriculture and horticulture. Without the soil organic chemistry provided by the life, death and cycling processes, the ability of the soil to support life itself diminishes. Providing structure is one of the many functions of the soil in supporting life and the assessment of this characteristic in soils is perhaps a measure for soil quality or health.

3.3 **Unprotected SOM**

SOM can be categorized in many ways, for example by size or dynamics. The unprotected organic compounds are important because they are quickly metabolised by a large array of bacteria and simple fungi which utilise the energy released for their growth. Most carbon in the soil starts off in this fraction (although a small amount of aromatic carbon compounds are fundamentally stable) and through a variety of processes some carbon goes through a process of stabilisation while the rest is respired as CO_2 or emitted as methane (CH_3).

Many studies have found that the light fraction (LFOM) or labile carbon fraction (sometimes called active carbon (Weil et al. 2003)) of SOM and particulate organic matter (POM) of SOM, especially coarse POM (>250 µm) are relatively easily decomposable and are greatly depleted upon tillage. This tends to highlight their relatively unprotected (biochemical and physical) status (Six et al. 2002). They consist of plant residues in various stages of decomposition, they have a high C:N ratio, a low net N mineralisation potential, a high lignin content and labile carbon is associated with microbial biomass and microbial debris (Six et al. 2002). Plant rhizodeposition is an important source of labile carbon, with root exudates accounting for, 5-10% (Jones et al. 2004), 21% (Mendes et al. 2011), 20% (Hütsch et al. 2002), of the carbon fixed by plants through photosynthesis. These root exudates are primarily sugars and secondarily amino acids (Jaeger et al. 1999). Labile carbon is used by soil microbes in the priming of SOM decomposition (Garcia-Pausas and Paterson 2011), also see thermodynamic factor below in Figure 1.19. Mycorrhizae trade this labile carbon for nitrogen, phosphorous, potassium, sulphate and water which the fungi collect at the soil-fungus interface (Garcia et al. 2016). Mycorrhizal fungi in turn contribute an important amount of carbon into the mycorrhizosphere, through a range of exudates including hyphal wall decomposition products (Jones et al. 2009, Garcia et al. 2016). The hyphae of arbuscular mycorrhizal fungi senesce to the glycoprotein, glomalin (Jones et al. 2009), which has been estimated to constitute as much as 5% of soil C (Treseder and Turner 2007). Glomalin is involved in the provision of soil structure as already mentioned and in soil aggregation, discussed below. Rhizosphere deposition of carbon is also thought to be involved in rhizosphere signalling perhaps by the flow of peptides (Jones et al. 2009), strigolactones (Ruyter-Spira et al. 2013) and flavonoids (Hassan and Mathesius 2012).

In converting unprotected SOM to protected, more stable SOM, three main mechanisms of SOM stabilization have been proposed: (1) chemical stabilization, (2) physical protection and (3) biochemical stabilization (Christensen 1996, Stevenson 1994) as cited in (Six et al. 2002).

3.4 **Physical protection by soil aggregation**

SOM is essential in the stabilisation process of soil particles. Soil biota such as AMF help stick soil particles together using glycoproteins and other organic compounds. This gluing process not only aids structure but aids protection of the organic matter itself by providing a physical barrier between the organic compounds and other soil biota which may consume such compounds (Edwards and Bremner 1967). This process of gluing soil particles together is known as soil aggregation. Soil aggregates are dynamic entities constantly changing regarding their biological, chemical and physical properties and in turn their influences on plant nutrition and health (Gupta and Germida 2015). Soil aggregates are constantly being formed and degraded at sometimes short temporal scales of less than a month in grassland (Wilcke et al. 2002).

SOM is physically protected from decomposition in free microaggregates less than 250μm in size (Six et al. 2002). This perhaps relates to the special architecture (Lehmann and Kleber 2015) of aggregates and chemical bonding of the organic compounds. Edwards and Bremner (1967) deduced from their work that organic compounds and inorganic soil particles are linked by polyvalent metals in these microaggregates (flocculation (Tisdall and Oades 1982)) see Figure 1.18, expressed by the formula: Clay-Polyvalent metal-Organic Matter, represented as (CL-PV-OM). Golchin et al. (1994) suggested carbohydrate-rich plant debris forms a major role in microaggregate formation. Microaggregates are stable to rapid wetting (Tisdall and Oades 1982) and tillage (Burns and Davies 1986).

A direct relationship exists between soil texture and the amount of silt-associated and clay-protected soil C, indicating a saturation level for silt and clay associated carbon (Hassink 1997, Six et al. 2002). This relationship was different between different types of land use, different clay types, and for different determinations of silt plus clay size class. Work in France by Arrouays et al. (2006) shows a strong relationship between percentage clay and soil organic carbon stocks in arable soils Figure 1.17.

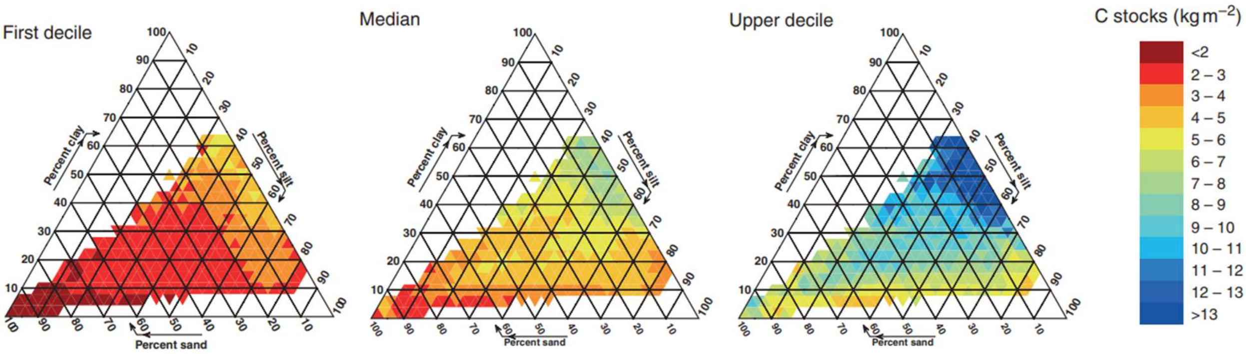
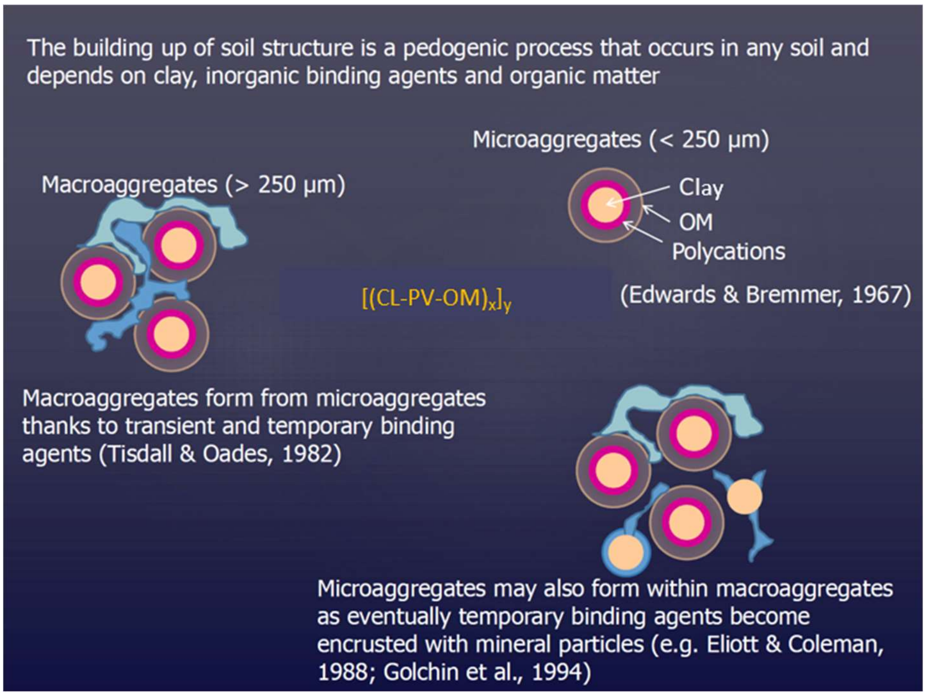


Figure 1.17 Projection of organic carbon stocks in the textural triangle (Figure 1.13). Median and decile values were calculated for each sub-triangle delineated by 4% classes of particle-size fractions, white areas indicate a lack of data (Arrouays et al. 2006).

Aggregates of larger soil particles such as sand will be disrupted by mild natural processes such as freezing and thawing, wetting and drying (Edwards and Bremner 1967).

Macroaggregates of >250µm are collections of microaggregates, less strongly bound than microaggregates (Edwards and Bremner 1967) see Figure 1.18. The nature of the microaggregate to microaggregate bonding and stabilisation (CL-PV-OM)$_x$ or [(CL-PV-OM)$_x$]$_y$ (in macroaggregates) depends largely on roots and hyphae, particularly AMF hyphae, and thus on growing root systems through a process of enmeshment and adhesion (Tisdall and Oades 1982, Rillig and Mummey 2006, Rillig et al. 2015, Morris et al. 2019). Decaying hyphae also release glomalin which facilitates adhesion (Jones et al. 2009, Garcia et al. 2016). Driver et al. (2005) found that 80 per cent of glomalin related soil protein (GRSP) was strongly bound in hyphae and spores and therefore not primarily delivered by secretion. Leading to the hypothesis of high turnover of fungal hyphae (Driver et al. 2005) supported by Staddon et al. (2003) who found in vitro hyphae half-life of 5-7 days. Macroaggregates, compared to microaggregates, are more easily destabilised by tillage (Tisdall and Oades 1982, Burns and Davies 1986) and provide the source of the nutrients which become available after tillage (Gupta and Germida 2015). Tillage is damaging to macroaggregated soil particles particularly when soil is left fallow with numerous tillage passes to remove plant growth (Tisdall and Oades 1982), due to shearing by implements, impact from rain drops, rapid wetting and drying, and oxidation of SOM.



The building up of soil structure is a pedogenic process that occurs in any soil and depends on clay, inorganic binding agents and organic matter

Macroaggregates form from microaggregates thanks to transient and temporary binding agents (Tisdall & Oades, 1982)

Microaggregates may also form within macroaggregates as eventually temporary binding agents become encrusted with mineral particles (e.g. Eliott & Coleman, 1988; Golchin et al., 1994)

Figure 1.18 Soil Aggregation, CL-clay, PV-polyvalent metal cations, OM-organic matter, [(CL-PV-OM)$_x$]$_y$ denotes microaggregation as a building block to macroaggregation (Bonifacio 2020).

3.5 **Bio-stabilisation and chemical stabilisation**

Biochemical stabilization is understood as the stabilization of SOM as a result of its own chemical composition (e.g. recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes in soil (e.g. condensation reactions which build chitin from glucose) (Six et al. 2002). This is consolidated by Kleber et al. (2011), who found no indication that materials with the characteristics attributed to highly biochemically stabilised products are a major constituent of organo-mineral associations with a mean turnover time of 680 years (Kleber et al. 2011). Therefore, old and stable SOM is not necessarily chemically recalcitrant.

Biochemical stabilization/protection of SOM occurs due to the complex chemical composition of organic materials. This complex chemical composition can be an inherent property of the plant material (referred to as residue quality) or can be attained during decomposition through the condensation and complexation of decomposition residues, rendering them more resistant to subsequent decomposition (Six et al. 2002).

Some have suggested that chitin, a component of fungal cell walls, reduces the rate of fungal tissue decomposition because it is relatively recalcitrant (Fernandez and Koide 2012). Fernandez and Koide (2012) examined the change in chitin concentrations of ectomycorrhizal fungal tissues during decomposition. Their results show that chitin is not recalcitrant relative to other fungal compounds in fungal tissues and that its concentration is positively related to the decomposition of fungal tissues (Fernandez and Koide 2012). Chitinase, an enzyme that breaks down chitin, activity decreased as age and N availability increased across the chronosequence of soil in Hawaii (Olander and Vitousek 2000) which indicates that recalcitrance may also be a function of soil fertility. Perhaps more fertile soils have ample available short chain carbon food, without the need to produce chitinase to decompose chitin, which is likely to be an energy intensive process?

However, there is now robust evidence that, under suitable conditions, appropriately adapted decomposer organisms have the ability to decompose materials previously presumed persistent and do so more quickly than previously anticipated. This includes polycondensed aromatics, alkanes in soil, fire-derived carbon, crude oil in sea water (Aldrett et al. 1997), oil in soil (Tibbett 2000, Tibbett et al. 2011) and even polyethylene (Yang et al. 2014). Also, contrary to previous assumptions, the decomposition of recalcitrant lignin is fastest at the early stages of decomposition, as long as it is easily accessible (not physically protected) and small organic molecules are available as a source of energy (known as the thermodynamic factor) to help mineralize the lignin (Lehmann and Kleber 2015). This leads to the proposition that the recalcitrance of organic matter in the soil is not linked to the innate degradability of the molecules but more the result of some combination of (1) the available energy in short chain carbon molecules (the thermodynamic factor), (2) the presence of the specific biota relevant to the decomposition process and their capacity to provide relevant enzymes such as lignase, chitinase and cellulase and, (3) lack of any protection afforded by the associations of the biopolymer molecules with the mineral surfaces available from the soil parent material (Figure 1.19). Indeed, the thermodynamic factor, where small organic molecules are necessary to provide the energy to break the molecular bonds of larger molecules, is thought to be a critical factor not considered by many studies looking at SOM decomposition to date (Lehmann and Kleber 2015). This suggests that building SOM is not just a case of adding carbon to the soil in the form of plant material, it needs to be stored and fixed in the soil, by soil organisms and protected by soil particles through the aggregation processes in Figure 1.18, otherwise it will be easily decomposed.

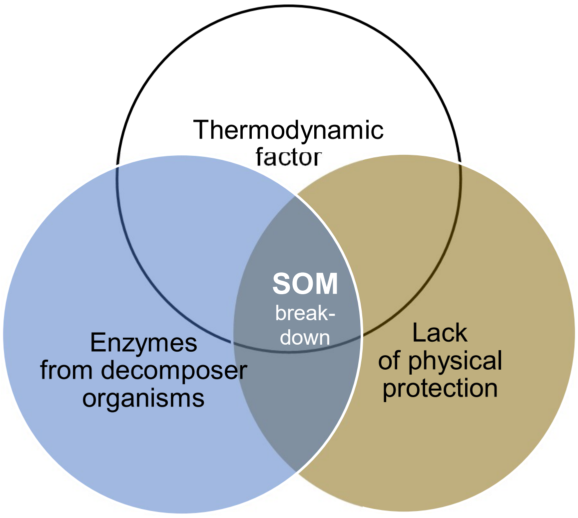


Figure 1.19 Proposition of conditions for SOM degradation (Bosatta and Ågren 1999, Lehmann and Kleber 2015)

3.6 **SOM turnover**

Carbon, the chemical building block of all organic matter, turns over in the soil as it moves through the soil food web (Scheu 2002)(Figure 1.22), with some processes resulting in its stabilisation and others in the production of carbon dioxide or methane. This is interesting from a greenhouse gas emission perspective, soil stability understanding and a food availability context. The influence of management practices on the quantity of organic matter in soil is vitally important both for the maintenance of soil functions, its influence on plant growth and for its impact on global carbon cycling and climate change. Six et al. (2002) developed a dynamic chart, Figure 1.20, for SOM circulation together with the general characteristics for any new or introduced plant material. The flow of carbon through SOM is part of a larger cycle of carbon through the whole Earth which is described as the Carbon cycle (Stevenson and Cole 1999).

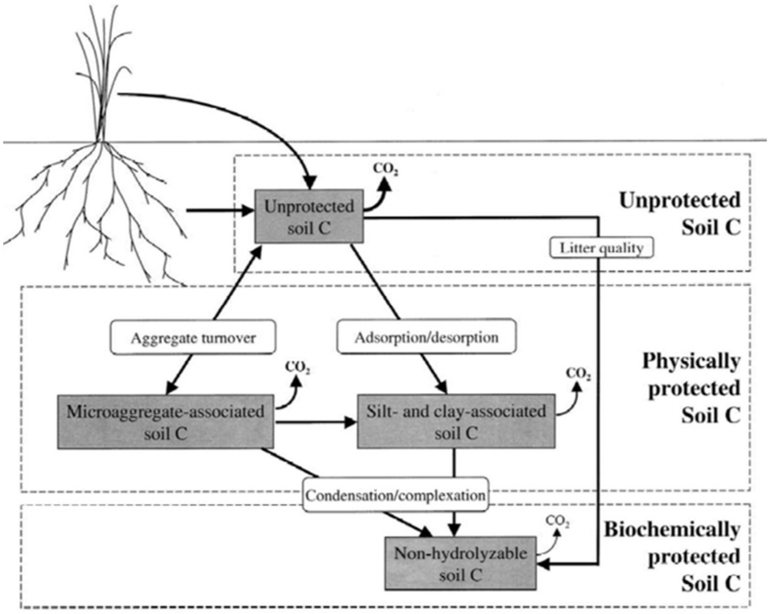


Figure 1.20 Conceptual model of soil organic matter (SOM) dynamics with measurable pools. The soil processes of aggregate formation/degradation, SOM adsorption/desorption and SOM condensation/complexation and the litter quality of the SOM determine the SOM pool dynamics (Six, Conant et al. 2002).

3.7 **SOM levels**

SOM is intricately involved in the functioning of soil particularly regarding physical stability. The level of SOM will have varying outcomes on soil physical properties. Looking at an extreme situation of pure wind-blown sand, there is little or no SOM, resulting in its inability to hold its shape when dry. The large particles will have weak attractive forces when wet or dry, contrasting with small clay particles which have strong attractive, van der Waals force, when dry due to their small particle size (Hu et al. 2015). SOM in both situations improve the functioning of the material by forming new chemical and molecular bonds with the particles as discussed above under aggregation. Perhaps instinctively organic matter can be seen to improve the soil, as Liebig and Doran (1999) discovered, farmers generally have a good perception of soil quality, but is there a suitable level of SOM content which ensures optimum performance?

Soil degradation by farming practices is a process intrinsically based on the lowering of the SOM level, such as, by intensive tillage/cultivation practices but also by other exploitative practices of farming which remove crop residues. The loss of organic matter from agricultural lands constrains our ability to sustainably feed a growing population and mitigate the impacts of climate change

(Machmuller et al. 2015). Loveland and Webb (2003) show a considerable concern that, if SOM concentrations in soils decrease too much, then the productive capacity of agriculture will be compromised by deterioration in soil physical properties and by impairment of soil nutrient cycling mechanisms.

Although soil scientists would expect to find different behaviour in different soils at different critical concentrations of SOM, it seems widely believed that a major threshold (in the UK) is 2% soil organic carbon (SOC) (ca. 3.4% SOM), below which, potentially serious decline in soil quality will occur (Loveland and Webb 2003). SOM is strongly linked to global carbon cycling and critically linked to soil properties and biogeochemical soil processes so its status is often taken as a strong indicator of fertility and land degradation (Manlay et al. 2007). SOM is clearly critical to the positive functioning of soils, however, a single critical threshold value for soil carbon content in temperate soils cannot be supported from the evidence available. Similarly, there has been a lack of evidence to support different critical SOC values for different soils under different land uses. The evidence available suggest that there might be an optimum or desirable range of SOM across a range of soil types, but Loveland and Webb (2003) found the evidence equivocal at best. However, Prout et al. (2020) have recently developed an index of SOC/Clay ratio using soil structural quality. It satisfactorily separates known woodland, grassland, ley grass (ley = short-term pasture) and arable soils into ratios according to: very good >1/8> good >1/10 moderate >1/13> degraded in Figure 1.21.

Considerably more quantitative investigation would be required to establish this clearly as SOM is not one static substance it is dynamic, and every sample will contain a collection of different organic carbon compounds. The debate on SOM will continue, if for no other reason than almost everyone sees it as a keystone indicator for soil quality or soil health. Loveland and Webb (2003) describe the nature of this indicator (total SOM or SOC, active/labile SOM or some fraction of it, etc.) will need further investigation if it is to be widely accepted in the long term, with the parallel implications for design, implementation and costs of soil monitoring frameworks.

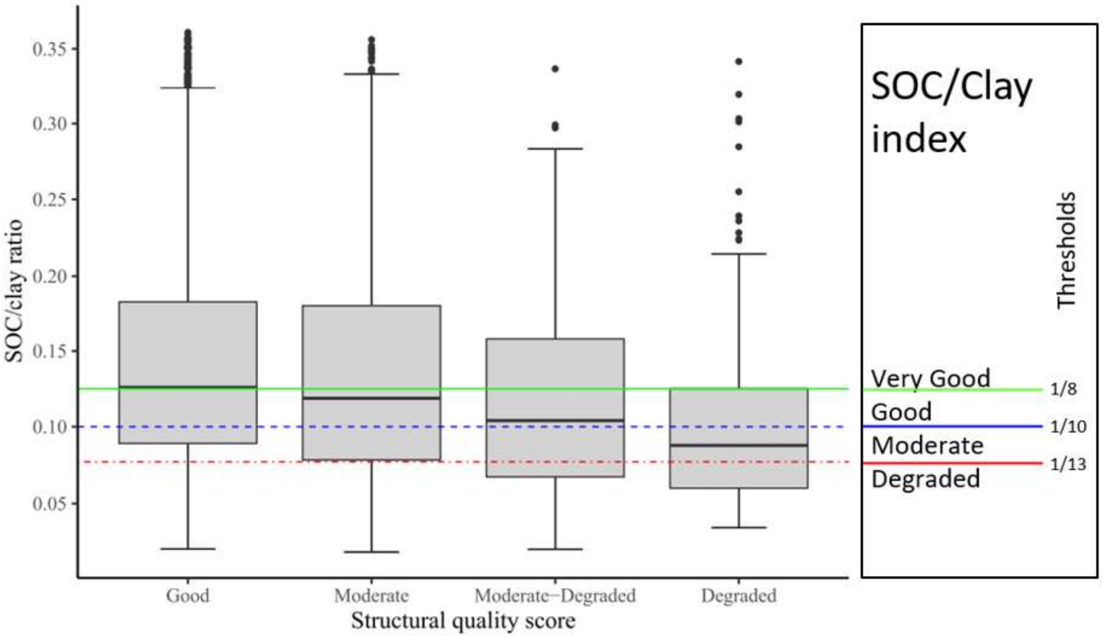


Figure 1.21 Box plots of soil organic carbon (SOC)/clay ratio for each structural quality score. Horizontal lines are SOC/clay thresholds: Solid green= 1/8, dashed blue = 1/10, dot-dash red= 1/13. Numbers of samples in each group were n = 2,250, 1,111, 229 and 208 for good, moderate, moderate-degraded and degraded, respectively (Prout et al. 2020). SOC/Clay index is shown on the right (Prout et al. 2020).

In December 2015 the French Government launched the 4 pour mille (4p1000 2015) initiative to increase SOM annually by 0.4%. The imperative has come out of an understanding of the crucial role that agricultural soils play in both food security and the climate crisis (4p1000 2015). The initiative was then further developed at the 21st Conference of the Parties to the UN Framework convention on climate change, held in Paris 2015, known as COP21 and forms part of the Paris Climate Agreement (Minasny et al. 2017). Adopted by the UK Government it highlights the ability of soils to store more carbon. The UK Government is currently working on plans for a new system to support agriculture with the potential for paying land owners to store carbon (CLA 2020, Finlay et al. 2021).

Management practices that account for both crop yield and SOM will likely lead to the long-term sustainability of all soils. Such management avoids soil compaction, strives to reduce soil disturbance, maximizes plant matter production through proper nutrient management and incorporates grass legume and herb forages into the crop rotation to facilitate increased in-situ deposition of plant matter belowground, which provides food for soil biota, Table 1.1. The historic levels of soil organic matter in global soils that developed under the influence of thousands of years of continuous grassland or forest (such as were seen in virgin Chernozem soils), may never be seen again. But the remaining soil organic matter can be managed better. Within the constraints of our agricultural land management practices and production systems, SOM can be increased as much as possible (Fuller 2010).

Table 1.1 Summary of key functions of organic matter in the soil

Function	Mechanism
Provides structure	Sticks soil particles together in an organised fashion with moisture and air by the action of e.g. mycorrhizal fungi, bacteria, meso and macro fauna (Leake et al. 2004, Frouz 2018)
Provides air and water ingress	OM feeds biota which arrange soil particles, adding structure by gluing particles together the gaps/pores between the structure allow air in (Leake et al. 2004, Lavelle et al. 2006, Frouz 2018)
Stores water avoiding drought	The physical lattice that is created by the soil biota provides hydrophilic molecules and holes for air and water to occupy, improving rainwater efficiency (Falkenmark and Rockström 2008, Abiven et al. 2009, Stroosnijder 2009, Fageria 2012)
Reduces flooding of rivers	As the soil absorbs more water it takes longer to percolate to the river therefore water from high rainfall events is buffered and becomes dispersed (Stroosnijder 2009)
Environmental regulator, particularly water quality	By filtering/denaturing pollutants and by reducing erosion and non-point source pollution (Lal 2008).
Stores nutrients	Nutrients are attached to mineral particles which are in turn protected by SOM in soil aggregates, SOM increases cation exchange capacity holding more minerals in soil reducing vulnerability to leaching (Fageria 2012) (Figure 1.18), SOM also stores the nitrate anion NO_3^- (Qian and Schoenau 1994).
Provides food for soil biota	Soil biota consume and breakdown SOM to provide nutrients for themselves and other organisms in turn, AMF and EMF access nutrients for plants in exchange for simple carbon compounds, (Kramer et al. 2012, Gougoulias 2014), soil biota provide services which are classified as soil functions (Bossuyt et al. 2004, Briones 2014)
Enhance biodiversity	There is a symbiotic connection between increased soil biodiversity and increased SOM and increase plant diversity (Heijden et al. 2008, Thiele-Bruhn et al. 2012).

Function	Mechanism
Stores Carbon for "the human climate niche" (Xu et al. 2020)	Dead plants, animals and sea creatures have formed old and ancient rocks, soils and peats, all of these resulted in the locking up of carbon, particularly in soil which are in permafrost (Schuur et al. 2008, Ostle et al. 2009, Scharlemann et al. 2014).
pH buffering	Increased SOM can act as a pH buffer particularly in acid soils (Magdoff and Bartlett 1985, Curtin and Trolove 2013), whereas the addition of lime can have negative consequences for carbon sequestration in acid soils possibly by increased microbial action (Ignacio Rangel-Castro et al. 2004, Rangel-Castro et al. 2005, Lal 2008)
Medium for plant support to enable food and fibre production	Soil aggregation provides architectural support for plants both enabling seedling establishment and root development, preventing soil erosion and soil compaction (Selby 1993, Lehmann and Kleber 2015).
Insurance against risks of future hazards	Higher SOM buffers crop yield against adverse weather and energy price shocks (Cong et al. 2014)
Suppresses soil borne plant pathogens	Soil amendments with low carbon availability suppress fusarium wilt by reducing nitrogen availability for the pathogen (Janvier et al. 2007, Senechkin et al. 2014, van Bruggen 2015). Mesofauna such as collembola feed off SOM but also feed on pathogenic fungi (Neher and Barbercheck 1998, Sabatini and Innocenti 2001)
Soil tills more easily	The soil particle to organic molecule bond is weaker than the soil particle to soil particle bond in clay soils except when the soil is in solution, higher SOM widens the range of soil water content that is tillable (Hu et al. 2015, Obour et al. 2018)
Warms soil faster	Darker colour of organic soils absorb light (Fageria 2012)
Prevents and remediates salinization	Due to reduced surface evaporation, less capillary action, increased biotic action in organic soils (Lax et al. 1994, Rao and Pathak 1996)

3.8 **SOM saturation deficit**

Some studies propose a limit to the amount of SOM a soil can hold due to soil aggregation in a given soil texture, with a given biotic system (land use) and in a particular climate (Hassink 1997, Six et al. 2002). Other studies have confirmed this (Stewart et al. 2007, Chung et al. 2010). Native soils may not indicate the maximum SOM a soil can hold due to natural deficits such as phosphorus or limitations to the cropping or tillage systems (Six et al. 2002). This leads to the proposition that a SOC saturation deficit can be calculated based on the full potential of the soil to sequester carbon less the actual current carbon stock (Angers et al. 2011, Beare et al. 2014). However not all studies show an upper limit to SOM accumulation (Orgill et al. 2017), which leads to the question is the upper limit beyond the scope of the study or is there no upper limit in such studies? The concept of a saturation deficit is particularly important in assessing carbon sequestration potential of soils for climate change mitigation purposes (Beare et al. 2014).

4. Soil biome and the community balance

The origin and quantity of plant inputs to the soil are the primary factors controlling the size and structure of the soil microbial community (Kramer et al. 2012). The soil is inhabited by a vast collection of organisms which comprise and live off the soil organic matter, bring in minerals from the surrounding rocks and aggregate them into particles, assimilate them for growth or exchange them with plants for sugars. One gram of soil contains as many as 10^{10}–10^{11} bacteria (Horner-Devine et al. 2003), 6000–50 000 bacterial species (Curtis et al. 2002) and up to 200m fungal hyphae (Leake et al. 2004). However, while it is widely recognized that microbes perform crucial roles in biogeochemical cycling, the impact of microbes on plant productivity and diversity is still poorly understood (Heijden et al. 2008, Barry et al. 2020) and there are many benefits to accrue from further investigations (Rillig et al. 2015). A review of microbial ecology in the rhizosphere by Philippot et al. (2013) highlights the future importance of research in this area suggesting great benefit from integrating reductionist and systems-based approaches in both agricultural and natural ecosystems.

Although the interaction between the different organisms is complex and only partly understood, the diagram below, Figure 1.22, describes the fundamental interaction of the species involved. This soil food web, collectively called the soil biome, forms a balanced level of plant, animal and soil organisms which are dependent on light, air, water and OM (food) as external inputs. Investigation of the relationships between microbial community composition and ecosystem functioning has received growing attention in recent years and it is now well recognized that microbial diversity affects ecosystem processes such as primary productivity (Heijden et al. 2008, Fierer 2017, Barry et al. 2020), organic carbon cycling, resistance to perturbations and bioremediation of degraded and contaminated soils (through detoxification of contaminants and restoration of soil physical, chemical and biological properties and processes) (FAO 2003). Soil microbes provide nutrients by mineralizing organic matter (Hodge et al. 2000), control soil organic carbon storage (Moorhead and Sinsabaugh 2006), contribute to the structural stability of soil aggregates (Abiven et al. 2009), suppress soil borne plant pathogens (Janvier et al. 2007, Senechkin et al. 2014, van Bruggen 2015) and, as a consequence, affect plant health and crop yield (Bonanomi et al. 2016).

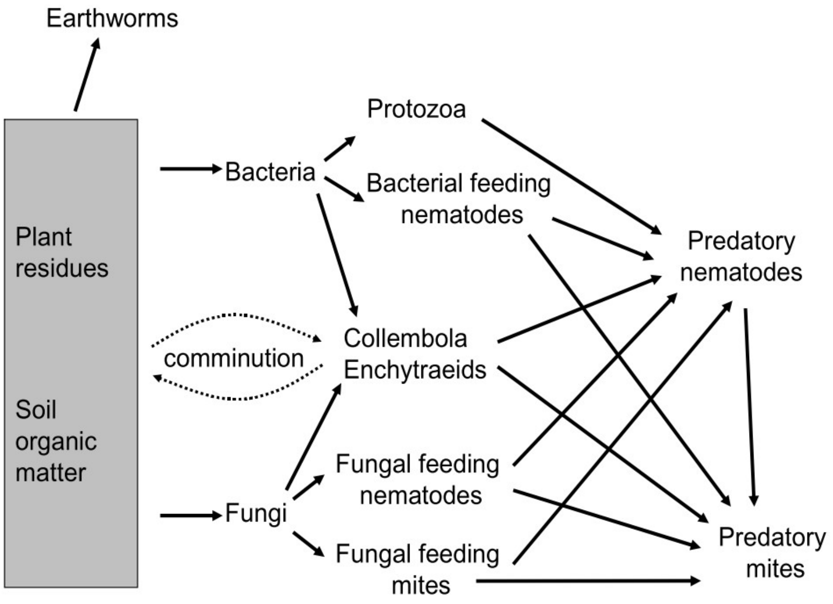


Figure 1.22 Decomposition of SOM shown in relation to the taxa of the soil food web. Taxa are sub-divided into trophic groups where relevant. Returns to the pool of soil organic matter in excreta and/or on the death of organisms are not shown (Stockdale 2006).

4.1 **Change in the soil biome with industrial agriculture**

If the diverse natural environments are disrupted by a farming system, whose primary method is the replacement of a diverse plant community with monocultures of annual crops, the soil biome will clearly adjust to new conditions and will reorganise itself to form a new equilibrium (Sugiyama et al. 2010, Hendgen et al. 2018). As farming has become more efficient there has been less by-product returned to the soil to feed the soil biology. Efficiency, the profit motive and synthetic inputs have disregarded any need to feed the soil life as the ecosystem services provided by the living soil were not valued. With a reduction in plant diversity and biomass returned to the soil, there will inevitably be less organic matter or energy to power the soil biome. Initially this will result in a lowering of the SOM as the soil food store is used up. Eventually a new balance is achieved reflecting the new lower level of annual biomass added to the soil and resulting in a lower level of SOM. As agricultural intensification occurs, regulation of soil functions through chemical and mechanical inputs progressively replaces the regulation through soil biodiversity, this is developed in Chapter 5. In the long term, the erosion of species and ecosystems that constitute important resources and support systems to human activities and well-being, will undermine sustainable development opportunities worldwide (FAO 2003).

4.2 **Outcomes for the soil biome**

Soil biodiversity *per se* may not be a soil property that is critical for the production of a given crop over short time horizons, but it may be vital for the continued capacity of the soil to support that cropping system (Doran 1994). This interaction of the biota can be thought of like the music of an orchestra. If dissected, the individual musicians give little clue as to what is possible when the orchestra is functioning together as a whole. The music of the soil is perhaps best observed as a functioning whole, a concept sometimes referred to as soil health or system health and again, developed in Chapter 5. The diagrams below develop the concept of the ecosystem services that these tiny creatures provide through their activities and characterise the range of biota that are involved. Indeed, Stockdale and Brookes (2006) say that studies of single soil organisms, while useful in specialized cases, e.g. Rhizobia and mycorrhizae, do not yield information on the functioning of the soil ecosystem. This is because most important soil processes, e.g., carbon and nitrogen mineralization, depend upon interactions between entire suites of organisms, many of which still await identification and most of which remain unculturable (Stockdale and Brookes 2006), Figure 1.23. Interactions between plants and microbes in the rhizosphere are of global importance to biogeochemical cycling (Philippot et al. 2009). Mycorrhizae as members of the soil community ameliorate plant mineral nutrition and contribute to soil aggregate formation (Smith and Smith 1997).

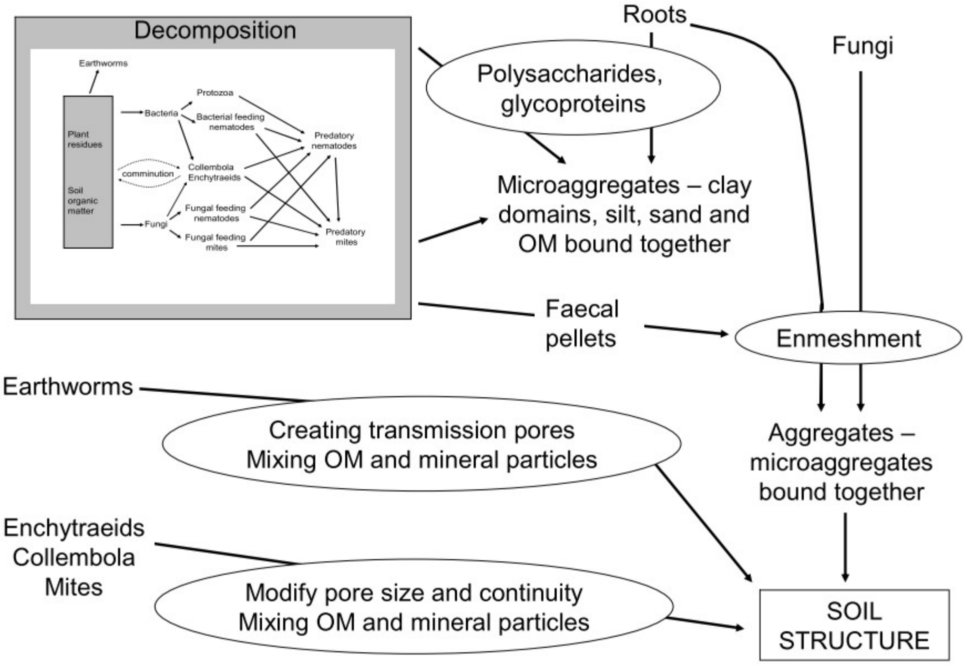
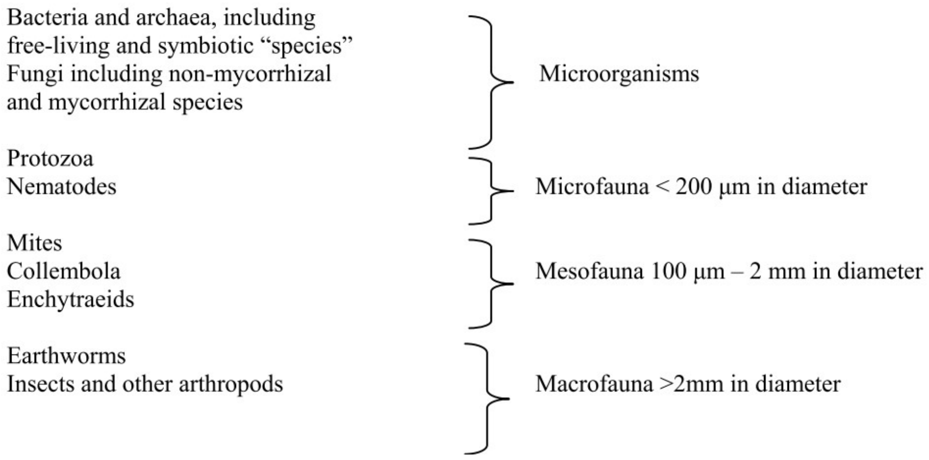


Figure 1.23 Soil structure development and stabilisation processes shown in relation to the roles of soil organisms (Stockdale 2006).

The soil life, particularly fungi, interact with the plants to form a huge plant feeding system, which make plant roots more effective by both extending their reach and sourcing nutrients unavailable to the plants on their own. The use of artificial fertilisers for over 160 years has resulted in these fertilisers replacing the function of the living soil to feed plants. Earthworms have long been known to characterise healthy soils, particularly since Darwin's last book on the subject (Darwin 1881). Earthworms are known to process large quantities of organic matter and create systems of burrows that aerate the soil and make it porous (Syers 1984). Plant community characteristics, such as declining diversity, indeed affect the structure of earthworm communities (Eisenhauer et al. 2009). Figure 1.24 categorises some of the key soil biota by size.



Bacteria and archaea, including free-living and symbiotic "species" Fungi including non-mycorrhizal and mycorrhizal species	Microorganisms
Protozoa Nematodes	Microfauna < 200 µm in diameter
Mites Collembola Enchytraeids	Mesofauna 100 µm – 2 mm in diameter
Earthworms Insects and other arthropods	Macrofauna >2mm in diameter

Figure 1.24 Size grouping of soil organisms by body width (Stockdale 2006).

5. Soil Health assessment

Soil type, texture and structure can be classified but what determines if a soil is healthy? As indeed it is possible to have a good soil that is not healthy and a poor soil which is healthy.

The activities of farming, agriculture and food production can be summarised into one word: health. The World Health Organisation defines human health as a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. It is not a static state, it is part of living processes and therefore dynamic in nature, it is a process of constant building up, so a healthy living growing system will need a constant input of energy to keep it alive and developing. Health is, likely to be, never perfectly achieved when the surroundings or environment are constantly changing. The ability of an organism to withstand these changes, shocks and stresses it experiences is often referred to as resilience. Resilience focuses on the return of the system to the equilibrium over time (recovery) (Doring et al. 2015). Another way of looking at the state of health is homeostasis. Homeostasis is the ability of a living organism to adapt as a response to change and then maintain its health: a dynamic equilibrium. The term 'homeostasis' was first described by the French physiologist, Claude Bernard, in 1865 (Cooper 2008) and the concept is explored in Chapter 5. In this was soil can also be viewed as a living organism or biome, a truly healthy soil will therefore be able to respond and benefit from change. Indeed, some have anecdotally described the soil akin to the inside of the cow’s stomach, if you imagine a stomach cut open, turned inside out and laid flat on the earth. This does give an interesting visual comparison.

Soil health is commonly defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (Lehmann et al. 2020). Measuring the parameters of soil health is not so straight forward as at first it may seem, as health is a dynamic process and involves the interaction of many actions and processes. As with any living organism, plant, animal or human for example, its ability to function can determine its state of health. This approach can be used with soil, by assessing the soil functions described in Table 1.1. Understanding that these functions are supplied by the soil organic matter means that any lack of function can be addressed through remediation of that soil organic matter. Remembering that SOM is a result of living processes described in the preceding sections, remediation will therefore involve developing the soil biota through a process of soil regeneration (Section 6).

Some of these functions provide public goods (Samuelson 1954, Musgrave 1959) as cited in (Dwyer et al. 2015), such as flood defence, through ecosystem services, which conveys the importance and value of, natural systems to society and the economy (Ehrlich et al. 1977, Ehrlich and Mooney 1983) as cited in (Dwyer et al. 2015)). Soil function in the context of public goods and ecosystem services is important, though due to the size of this subject it is only touched upon here.

5.1 **Soil Organic Matter and Soil Organic Carbon as a measure of Soil Health**

Generally, the higher the SOM level in the soil the better the overall soil function, there is no fixed level that is good or bad so SOM cannot be used as an absolute indicator between soils (Loveland and Webb 2003). The direction or movement in SOM can be used, a positive change will indicate an improvement in the health of the soil. There is an apparent contradiction that healthy soils need not be high in SOM. The possible confusion arises over the quantity of living biota in the soil and the soil textural factor (see above). A fully functioning living soil may require a good deal of organic matter just to live and it may turn this organic matter into low ratio C:N compounds that are easily degraded and consumed and harvested, therefore making it difficult to increase the absolute level of carbon. In this instance the cycling of carbon in the soil is high and the biological activity high, leading to a healthy soil. As described in section 3 it is the cycling or turnover of carbon in the SOM that is important rather than an absolute level.

There has been large variability in the measurements of SOM due to inaccuracies and variations in the loss on ignition test (LOI) (Hoogsteen et al. 2015). Different temperatures are often used by different laboratories from 430-550°C when conducting LOI, at higher temperatures carbonates are released from calcareous soils and clay soils release tightly bound water. It is therefore important to document the methodology.

Soil organic carbon is the carbon in the soil organic matter and is widely recognised and historically assumed as being 58% SOM (Bianchi et al. 2008, Pribyl 2010). However due to variations in SOM constituents and in tests used to measure SOM this figure of 58% from the 19th century is disputed and a review of 481 cases showed a median conversion factor of 53% (Pribyl 2010). The Dry combustion (Dumas) test (Grewal et al. 1991) measures the total carbon directly.

5.2 **Soil tests and assessments**

There are a variety of soil tests that can be used to assess different characteristics of soil including SOM, these are described below in Table 1.2.

Table 1.2 Standard Soil Tests

Test Name (ref)	Measure of Soil Characteristic	Advantage/Disadvantage
Basic Chemistry Tests		
Soil pH **(Rowell 1994)**	Measure of acidity/alkalinity, indicates availability of nutrients and plants favouring this pH	Soil pH can be a predictor of soil microbial community composition (Fierer and Jackson 2006), low cost/
P **(Olsen 1954)** **K, Mg** **ammonium nitrate extraction method (Rowell 1994)**	Measure of water extractable nutrients	Low cost / misses the nutrients which are more strongly bound to soil
Electrical Conductivity **(Rowell 1994)**	Measure of salt concentration in soil	Low-cost
Cation Exchange Capacity **(Rowell 1994)**	Assesses soil ability to supply cation nutrients to plants and perhaps microaggregation potential	Routine soil test

Test Name (ref)	**Measure of Soil Characteristic**	**Advantage/Disadvantage**
SOM/SOC tests		
Loss on ignition @430ºC **(Ball 1964)**	Measure of oxidisable organic carbon, (caution with CaCO3 and clay soils must be taken), gives indication of SOM	Universally accepted becoming low-cost / vulnerable to misuse in calcareous soils and by using different furnace temperatures in clay soils. When used to measure change over time some errors are removed.
Labile Carbon **(Weil et al. 2003, Schindelbeck 2016)**	Oxidizable carbon (in response to changes in soil management)	Early indicator of soil health change/ the test has yet to be fully evaluated
Dry combustion (Dumas) test **(Grewal et al. 1991)**	Soil Organic Carbon (calculated from total carbon less total inorganic carbon)	Nitrogen and Sulphur can also be analysed/higher cost than LOI for SOM determination and care with sampling in lab is important
Near Infra-Red Spectroscopy **(Hartmann and Appel 2006, Terhoeven-Urselmans et al. 2006)**	Organic Compounds	Sample analysis quick and low-cost / calibration of machines not yet available for soil
Bradford assay **(Rosier et al. 2006, Janos et al. 2008, Koide and Peoples 2013)**	Measure glomalin related soil proteins (GRSP) produced by AM fungi	Non frequent lab-based test/there is some doubts as to the accuracy of this assessment due to occasional confounding by other materials
Soil Nitrogen		
Soil Protein **(Hurisso et al. 2018)**	Rapid Soil Health Indicator of Potentially Available Organic Nitrogen	
SNS soil nitrogen supply test **(Knight 2006)**	Soil mineral nitrogen available to plants	
Dry combustion (Dumas) test see above	Total soil nitrogen	
Soil Biology		
Earthworm assessment **(Brown 2017) (USDA 2020)**	Indicator of available food and good environment for living biota	Low-skilled operator / time consuming and accuracy dependent on timing

Test Name (ref)	Measure of Soil Characteristic	Advantage/Disadvantage
Berlese-Tullgren Funnel **(Smith et al. 2008)** **(George et al. 2017)** **(Tilling 1987)**	Counts numbers of mesofauna and macro fauna	Good indicator of soil health/High skill for identification & time consuming in sorting and counting individuals
The Winkler extractor **(Tilling 1987, Smith et al. 2008)**	Counts macrofauna numbers	Good indicator of soil health/high skill for identification and time consuming
DNA extraction and sequencing **Meta barcoding** **(Oliverio et al. 2018)**	Measure of species diversity	High volume of information and becoming low-cost/ measures quantity of DNA which does not relate to biomass or abundance of an organism
PFLA Phospholipid Fatty Acid Analysis (Frostegård and Bååth 1996)	Snapshot of the soil microbial community	The same technique can be used for both fungal and bacterial biomass, allowing comparison/time consuming
Soil Respiration, CO_2 **(USDA 2020)**	Measure of total living biomass	Gives a measure of living aerobic biota / accuracy dependent on expensive equipment with highly skilled operators
Various staining methods with microscopy **(Vierheilig et al. 2005, Morris et al. 2019)**	Visualisation of arbuscular mycorrhizal fungi development in roots	Various staining methods exist depending upon research question asked/time consuming lab-based work
Hyphal traps **(Wright and Upadhyaya 1999)**	Assessing AMF over a growing season	Lab based assessment non routine/some doubt of Braford assay (see above)
General Assessment of soil quality/state/health		
Nematode communities **(Bongers and Ferris 1999)**	Measure of soil biota balance	In development as a measure of soil health
Circular Chromatography **(Kokornaczyk et al. 2017, Ford et al. 2021)**	Overview of soil condition	Low-cost qualitative soil health test/further research is needed to verify the interpretation of the test
Soil Physical Function		

Test Name (ref)	Measure of Soil Characteristic	Advantage/Disadvantage
Water infiltration **(USDA 2020)**	Measure of permeability, pore space, indicator of structure, indicator of liability of soil to flooding	Simple but time consuming
Penetrometer assessments **(Utset and Cid 2001)**	Measure or resistance to pressure, indicator of compaction or compacted layers and structure	Low-cost / inappropriate for stony soil, confounds soil structure and cultivation effect
Bulk density measurements **(USDA 2020)**	Measure of pore space, indicator of structure and water holding capacity	Widely recognised/ time consuming, importantly enables calculation of SOC per hectare from mass of soil
Soil aggregate stability with rapid wetting (Slake test) **(Arshad et al. 1997, USDA 2020)**	Qualitative indicator of soil particle aggregation by exposing soil to rapid wetting	Visually simplistic, low-cost / accuracy operator dependent
Visual Evaluation of Soil Structure (VESS) **(SRUC 2020)**	Combination of soil properties	A formalisation of common practise of digging soil to assess structure and general health / subject to operator
Satellite imagery		
NDVI **(Carlson and Ripley 1997)**	Soil health through plant activity	Historic data readily available, ease of access/context needs adding
Soil brightness (Caloz et al. 1988)	Light reflectance from soil (used to clarify any interaction with NDVI (Gilabert et al. 2002))	Ditto/relevance to standard tests is currently unknown?
Plant Quality tests		
Plant bioassay **(Tothill and Turner 1996)**	Measure of toxicity in the soil	Low-skill to set up for qualitative data/difficult to achieve quantitative data?
Brix test, refractometer **(Marigheto et al. 2006)**	Refraction of light to give plant sugar level, giving an indicator of plant health	Low-cost low-skill / inaccurate, needs degree of strength in operator
Independent Soil Test Suites		
Comprehensive Assessment of Soil Health (Schindelbeck 2016)	Range of soil tests aimed at assessing overall soil health	Useful reference for DIY soil testing and lab. based tests/US based

Test Name (ref)	Measure of Soil Characteristic	Advantage/Disadvantage
Soil Quality test kit (USDA 2020)	Range of soil tests aimed at assessing overall soil health	Useful reference for DIY soil testing/US based

Each test needs to be repeated over time to observe the dynamic impact of crop management practices, there is no single test that assesses soil health in either a scientific or agricultural context. There are however a range of commercial tests that aim to address soil health through various combinations of the above measures such as NRM's Soil Health and Soil Carbon Audit, Soyl's Soil life, Hutchinson's Ominia, SoilOptics and Soil Essential's Biotest, all of which are in the development phase and being explored by land managers, none have been adopted on a large scale.

There are also several farmer targeted tools and assessments that have recently been developed following grower and farmer interest in the subject. They are available through the Agriculture and Horticulture Development Board (AHDB) and the Organic Research Centre (ORC). They include an Introduction to soil biology (AHDB), healthy grassland soils pocketbook (AHDB) the basics of soil fertility (ORC) and give a good descriptive and practical, first principles, access to farm soil health. Initiatives such as Catchment Sensitive Farming have also engaged with farmers to highlight the impact of farming practices on soil, water and environment both on and off farm.

5.3 **A perceptive approach to Soil Health assessment**

The soil tests mentioned in the previous section can build a picture of soil health, educating and inspiring the observational skills of the land manager. The assessments also provide tools for continual assessment to help calibrate these perceptive skills (Odendo et al. 2010). A farmer, grower or landowner may find it hard to observe the slow degradation of soil as a result of a cropping system which does not have gross soil impacts. Furthermore, from one generation to another (one manager to another) there may be a problem of shifting baseline syndrome, where the new generation sets their starting point at the end point of the old. If the end point from the old generation is already degraded the previous degradation is lost or ignored (Pauly 1995). Which highlights the need for objective measures? The collation of a complete picture of observational soil health indicators together with soil tests will offer the agriculturalist signs of degradation and conversely signs of positive improvement. Detailed knowledge of the carbon flow in terrestrial ecosystems is a prerequisite for understanding ecosystem services and for managing agricultural systems in a sustainable way (Kramer et al. 2012). In Quantum Physics first developed by Max Planck, the act of observing or measuring changes reality or even brings it into existence (Radin et al. 2013). One needs to be conscious that the act of measuring has an impact itself – this is extremely relevant for soil science and soil ecology. Using observational senses can be a less intrusive method of soil assessment. Indicators such as, weed species, soil's reaction to high rainfall events (natural flood management (NFM)), variation in yield across fields, workability of the soil, soil colour, pests and disease and animal health (Odendo et al. 2010). These indicators can be used with a background knowledge of geology, climate, cropping and grazing histories, external inputs and management practices. Innate knowledge particularly of indigenous, rural or agrarian populations, is valuable and an entry point for soil management improvements (Barrios and Trejo 2003, Odendo et al. 2010, Ansong Omari et al. 2018). The background information can usefully be arranged onto maps to help access and aid interpretation. Through the interaction of these indicators, it is possible to perceive the health of the soil which is not directly observable (as by directly observing it changes the very nature of it). The homeostasis of the soil biome is perceived by these indicators when an extreme change is experienced, particularly climate, though also impacts of heavy traffic such as a combine harvester or cattle treading/poaching, as well as high levels of chemical pesticides or fertilisers.

6. Soil Regeneration

Soil regeneration is the improvement in function of degraded soil. The previous section describes how soil function emanates from soil organic matter and therefore soil regeneration or remediation will need to focus on developing the SOM, more specifically growing the life in the soil that generates the aggregated SOM. Sustainable management of natural resources involves the concept of using, improving and restoring the productive capacity and life support processes of soil, the most basic of all natural resources (Lal and Stewart 1992). Some indicators for restoring damage caused by intensive farming are given in Figure 1.25, adapted from (Lal and Stewart 1992). The condition of our soils ultimately determines human health by serving as a major medium for food and fibre production and a primary interface with the environment, influencing the quality of the breathable air and drinking water (Power 2010, Dwyer et al. 2015). There is a clear linkage between soil quality and human and environmental health. As such, the health of our soil resources is a primary indicator of the sustainability of our land management practices (Weiner 2004).

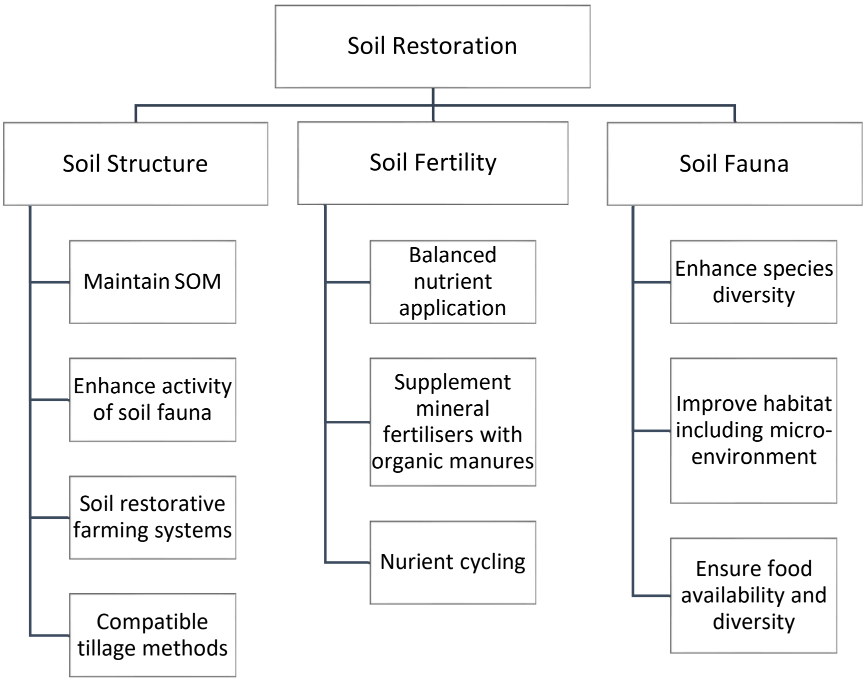


Figure 1.25 Approaches to restoration for soils degraded by intensive farming (Lal and Stewart 1992)

Weiner (2004) says that most current biological problems in agriculture occur, or are realised, at the higher levels of organization: populations, communities and ecosystems. Also, that these are the levels addressed by the science of ecology rather than other biological sciences and therefore ecology will by necessity become the central science of agriculture. Agricultural production will be a form of applied ecology or ecological engineering, Weiner also says this change in perspective has major implications for agricultural research. It brings the discussion of the assumptions of a research programme into the open and forces researchers to prioritize among potentially conflicting objectives. It sees agricultural strategies in terms of trade-offs, rather than improvements, and it suggests that agricultural research needs to be bolder and more ambitious if it is to solve the most important problems facing us in the new century (Weiner 2004).

If these two problems of soil degradation and organizational disfunction, which Weiner alludes to, are brought together with the understanding that soil organic matter is critical in this area, from previous sections, then solutions to soil regeneration can be found by bringing SOM positive interventions into soil restorative farming systems as mentioned by Lal in Figure 1.25.

7. Weeds as an indicator of Soil and System Health

Weeds, plants growing where they are not wanted and in competition with cultivated plants, have been vilified for centuries (Hill and Ramsay 1977) and are the single most important issue facing farmers (Wortman et al. 2010, OKNetArable 2017) . It is also thought to be one of the most important factors restraining conventional farmers from converting to agroecological and organic practices. Conventional farming systems cure weed problems by the use of agrochemicals, whereas organic farming systems control weeds by a collection of preventative methods often tuned to the specific farming system. Amongst the farming community, weeds have long been thought of as an indicator of soil conditions such as water-logging, compaction, acidification, high fertility and type of soil amendments used (Dale et al. 1965). Weeds, in an agroecological context, can be put into three major groups in this respect: 1) Those living on acid soils, which have resulted from over use of artificial fertiliser, thus causing soil acidification (e.g. genus Polygonum); 2) the pioneers (particularly perennials (Hill and Ramsay 1977)) that make use of crusts or hard pans, as a consequence of soil degradation caused by loss of SOM (e.g. Rumex (docks) and Elymus repens (couch grass)); and 3) those following human interventions or particular farming systems such as Avena fatua/sterilis (wild oats)) and Sinapis arvensis (charlock).

Growth characteristics of weeds may be an equally important indicator, Fredrick Clements (1920) as cited in (Hill and Ramsay 1977) said "Each plant is an indicator. This is an inevitable conclusion from the fact that each plant is the product of the conditions under which it grows and is thereby a measure of these conditions. As a consequence, any response made by a plant furnishes a clue to the factors at work upon it".

Crop productivity has been forefront in the context of agricultural weed management. Some farming systems, as already mentioned, have favoured the proliferation of certain weed species where the farming systems coincides with the weed’s own cycle and reproductive mechanisms with consequential detrimental effects on crop productivity. Examples of such systems include reduced or zero rotation, heavy use of animal manures (Wortman et al. 2010) and use of a mouldboard plough (Murphy et al. 2006) which lead to narrow weed species richness. Crop yield losses from increasing weed density are reduced by higher crop population and narrower crop row width (Wilson et al. 1995, Mertens 2002, Olsen et al. 2005) and vary with geographic location, crop species, weed species and sowing date (Milberg and Hallgren 2004, Sim et al. 2007).

Diversity of weeds prevents a rapid accumulation of a single weed species especially through diverse rotations (Wortman et al. 2010) and reduced tillage (Murphy et al. 2006). Ryan et al. (2009)

found in an experiment in the US that whilst organic and conventional system yields were similar the number of weeds in the organic system were substantially higher therefore retaining biodiversity. Recent research has shown many small diverse weeds can have little impact on yield whilst being beneficial for wildlife (Adeux et al. 2019).

Selected soil quality biological indicators were associated with potential weed-suppressive activity in soil when that soil was managed for high organic matter content under reduced tillage systems (Kremer and Li 2003, Stockdale and Watson 2009). Amending the soil with organic inputs in reduced input or organic farming systems can also influence seed persistence and weed seedbank levels (Gallandt et al. 1998, Fennimore and Jackson 2003). The results presented by De Cauwer et al. (2011) showed evidence for a short-term effect of the type and quality of organic amendments on the weed seed bank; seed bank numbers were higher in plots amended with cattle slurry than in plots amended with compost with low C:N ratio (De Cauwer et al. 2011). Inputs of organic matter can produce reduction of *Capsella bursa-pastoris* (shepherd’s purse) and *Urtica urens* (burning (stinging) nettle) (Jackson et al. 2004).

Predation of seed on the ground (for example by birds, rodents and macro fauna) in arable fields can be as high as 1000 seed/m2/day and may selectively influence the quantity of seed of particular herb species that enters the soil seed bank (Honek et al. 2003). It has been suggested that weed seed decomposition by microbes plays an important role in reducing the persistence of the soil weed seedbank (Chee-Sanford et al. 2006, Wagner and Mitschunas 2008). This can be affected by soil N levels depending upon weed species (Davis 2007). Land management history and soil microbial community composition have been linked to weed seed decomposition (Davis et al. 2006). Fungal feeding collembola can increase seedling emergence of certain weed species (Mitschunas et al. 2008). Weeds appear to be a good indicator of soil and system health (Barrios and Trejo 2003, Odendo et al. 2010, Ansong Omari et al. 2018), however, the great number of factors that influence weed seed bank make this phenomenon so variable over time making a consistent result difficult. These variables include location, weed species, soil quality, cropping systems and previous cropping.

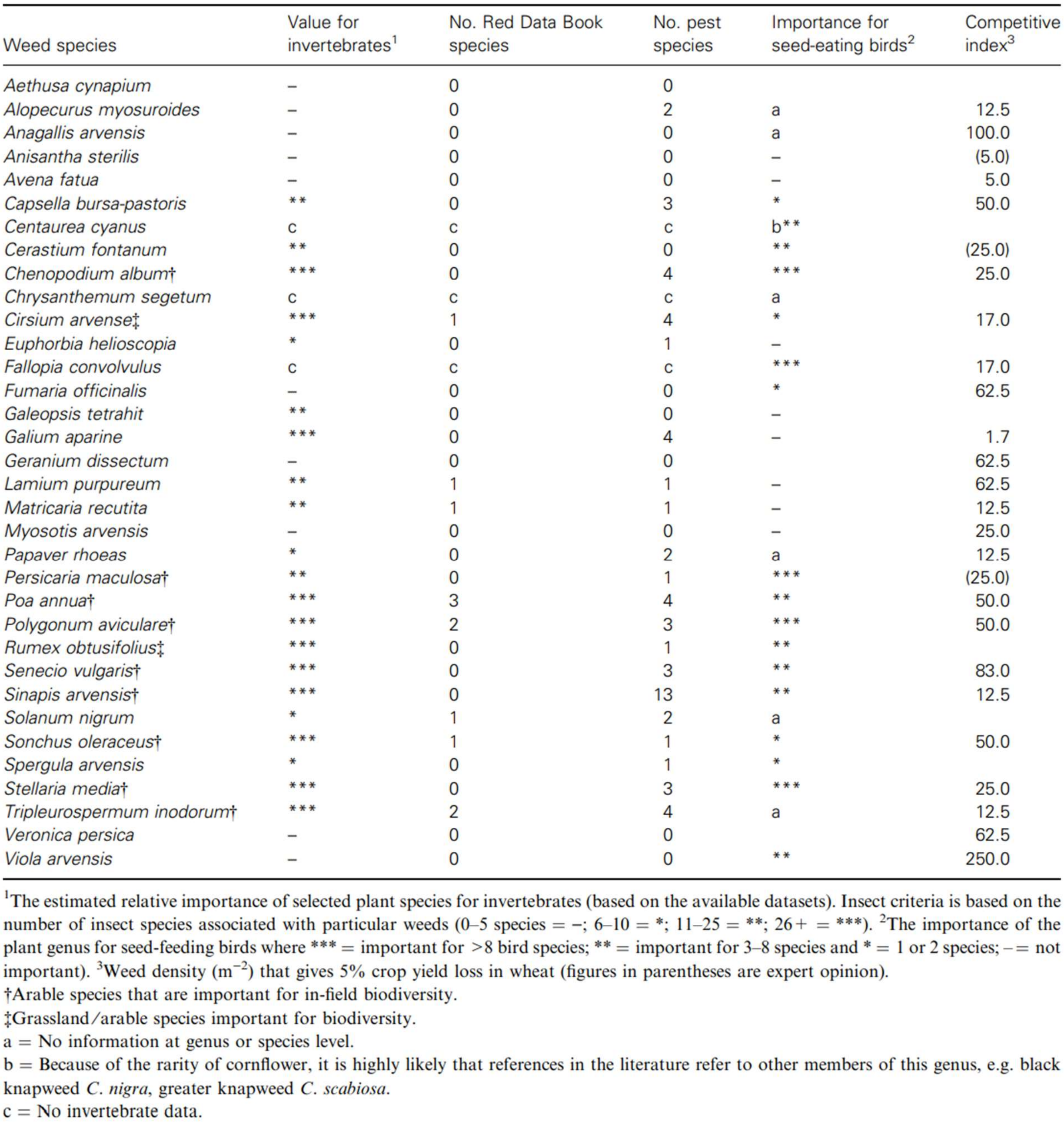
Weeds can be virtuous and supply important provision of many ecosystem services (Hill and Ramsay 1977), though this has been overlooked because some agriculturalists prefer numerical data to complex biological statements (Holzner 1982). Weeds can provide increased plant root community dynamic to facilitate soil development (Mueller et al. 2013), add root necro-mass to increase soil carbon, provide root exudates to feed soil fungi (Leake et al. 2004) and produce flowers for insect pollinator services particularly bees which have declined by 59% in 61 years in the

US (Bretagnolle and Gaba 2015). Weeds provide other sources of food as seeds for insects, in turn farmland birds can feed on both insects and seeds (Storkey and Westbury 2007, Gilroy et al. 2008) and leaf litter to feed soil fauna (Frouz 2018). Post-harvest weeds can provide soil cover before tillage for the following crop is undertaken; reducing nitrate leaching and soil erosion (Moreau et al. 2020) and providing a bridge for arbuscular mycorrhizal fungi between annual crops, importantly in non-mycorrhizal crops (Stockdale and Watson 2009). Storkey (2006) showed two functional groups of weeds (1: A. myosuroides, P. rhoeas, T. inodorum; and 2: C. album, F. convolvulus, P. aviculare, S. arvensis) are bio diversely important to birds and invertebrates while having little competitive effect on Winter wheat. Table 1.3 shows a range of weeds with their impact on biodiversity and their crop competitiveness (Marshall et al. 2003).

Weeds have been used as an indicator of ground water presence and quality (Chikishev 1965) as cited in (Hill and Ramsay 1977)). Weeds also have important nutrient value for livestock and wildlife, examples of such are dandelion (Taraxacum), nettle (Urtica dioica), creeping thistle (Cirsium arvense) and broad-leaved plantain (Plantago major) (Fairbairn and Thomas 1959).

Weed management is a critical and complex subject affecting crop productivity and ecosystem services. Weed burden on annual crops is affected by many factors: including crop species and variety, crop population density, sowing date, crop row width, geographic location, weed species and diversity, crop rotation, fertilisation method and tillage (Milberg and Hallgren 2004). Some weeds can make an important contribution to soil regeneration and biodiversity recovery whilst having little or no impact on yield (Adeux et al. 2019).

Table 1.3 The importance of a representative list of common weed species for invertebrates and birds and their economic importance in terms of crop yield loss (Marshall et al. 2003)



Weed species	Value for invertebrates[1]	No. Red Data Book species	No. pest species	Importance for seed-eating birds[2]	Competitive index[3]
Aethusa cynapium	–	0	0		
Alopecurus myosuroides	–	0	2	a	12.5
Anagallis arvensis	–	0	0	a	100.0
Anisantha sterilis	–	0	0	–	(5.0)
Avena fatua	–	0	0	–	5.0
Capsella bursa-pastoris	**	0	3	*	50.0
Centaurea cyanus	c	c	c	b**	
Cerastium fontanum	**	0	0	**	(25.0)
Chenopodium album†	***	0	4	***	25.0
Chrysanthemum segetum	c	c	c	a	
Cirsium arvense‡	***	1	4	*	17.0
Euphorbia helioscopia	*	0	1	–	
Fallopia convolvulus	c	c	c	***	17.0
Fumaria officinalis	–	0	0	*	62.5
Galeopsis tetrahit	**	0	0	–	
Galium aparine	***	0	4	–	1.7
Geranium dissectum	–	0	0		62.5
Lamium purpureum	**	1	1	–	62.5
Matricaria recutita	**	1	1	–	12.5
Myosotis arvensis	–	0	0	–	25.0
Papaver rhoeas	*	0	2	a	12.5
Persicaria maculosa†	**	0	1	***	(25.0)
Poa annua†	***	3	4	**	50.0
Polygonum aviculare†	***	2	3	***	50.0
Rumex obtusifolius‡	***	0	1	**	
Senecio vulgaris†	***	0	3	**	83.0
Sinapis arvensis†	***	0	13	**	12.5
Solanum nigrum	*	1	2	a	
Sonchus oleraceus†	***	1	1	*	50.0
Spergula arvensis	*	0	1	*	
Stellaria media†	***	0	3	***	25.0
Tripleurospermum inodorum†	***	2	4	a	12.5
Veronica persica	–	0	0		62.5
Viola arvensis	–	0	0	**	250.0

[1] The estimated relative importance of selected plant species for invertebrates (based on the available datasets). Insect criteria is based on the number of insect species associated with particular weeds (0–5 species = –; 6–10 = *; 11–25 = **; 26+ = ***). [2] The importance of the plant genus for seed-feeding birds where *** = important for >8 bird species; ** = important for 3–8 species and * = 1 or 2 species; – = not important). [3] Weed density (m^{-2}) that gives 5% crop yield loss in wheat (figures in parentheses are expert opinion).

†Arable species that are important for in-field biodiversity.

‡Grassland/arable species important for biodiversity.

a = No information at genus or species level.

b = Because of the rarity of cornflower, it is highly likely that references in the literature refer to other members of this genus, e.g. black knapweed *C. nigra*, greater knapweed *C. scabiosa*.

c = No invertebrate data.

8. Cropping Systems' impact on Soil Health and Productivity

Thinking of the farm as a system sounds obvious but is not always an intuitive practice. Central to the idea of a systems approach, as described by Spedding (1979), is that "one must understand the system before one can influence it in a predictable manner". This infers understanding boundaries, feedback loops and in particular "the behaviour as a whole in response to stimuli to any part" Spedding (1979). This sits very comfortably with the idea that ecology will be central science of agriculture this century (Weiner 2004). Ecology is the study of the interaction of living things with their environment, which involves the understanding of living environmental systems or ecosystems. As farms are living systems it seems there is congruence between the systems approach to agriculture and ecology as its central science. Various approaches to improving modern cropping ecosystems are investigated below.

8.1 **Perennial cropping**

Whilst afforestation isn't strictly farming, veteran trees can make an important contribution to farm systems (Read 2000, Fay 2002). It is also important to remember that trees would have formed a much more dominant part of our landscape beyond our current experiences, a phenomenon called the shifting baseline syndrome referred to above (Pauly 1995). Whilst there has been a sharp decline in wood-pastures in Europe, their ecological values are broad (Plieninger et al. 2015).

It is widely understood that reintroducing permanent cropping to annual cropping systems is the most effective way to add carbon to the soil (Powlson et al. 2011, Paustian et al. 2016) and therefore improve soil health (section 5 above). Facilitated through the improved root dynamics of plants with longer life cycles than plants in short season annual crops (Goss and Watson 2003).

Permanent pasture is a form of perennial cropping that can provide important ecosystem services (Asbjornsen et al. 2014), including storage of important quantities of C and making a valuable contribution to future C sequestration. Culman et al. (2010) point out that in Kansas, USA, native prairie pastures have been harvested every year for 75 years without fertilisation or decline in yield or soil fertility, whereas adjacent annual crop production has resulted in declining soil fertility and increasing inputs of fertilisers to maintain yields.

Planting trees in pasture has been found to have a deleterious effect on SOM (Upson et al. 2016). In their study, fourteen years after planting trees the woodland increased carbon storage as biomass, but about 37% of the increase in above ground carbon storage was offset by the soil carbon losses at just 0–100mm soil depth. Which suggests care in the siting and density of tree planting is important. Planting trees and removing sheep on improved upland grassland can have positive soil impacts in natural flood management, reducing water runoff by up to 78% (Marshall et al. 2014). Trees provide shelter for animals improving their welfare as well as increasing biodiversity.

8.2 **Agroforestry**

Agroforestry is a concept that aims to utilise the benefits of mixing trees with farming and in the 1970s was brought from the realm of indigenous knowledge into the forefront of agricultural research, being promoted widely as a sustainability-enhancing practice that combines the best attributes of forestry and agriculture (Bene et al., 1977; Steppler and Nair, 1987) as cited in (Sanchez 1995). Both silvo-pasture (grazing with trees and hedges) and silvo-arable (annual cropping with trees) agroforestry offer opportunities to benefit from the inclusion of trees in cropping and grazing systems. These result in ecological and economic improvement (Burgess and Rosati 2018). Whilst the benefits are apparent the high cost of manual labour in Europe is a disincentive to inclusion of fruit and nut trees into traditional agricultural systems (Smith et al. 2012).

Figure 1.26 Agroforestry systems A. Silvo-arable system of apple trees in 24m rows with organic cereal rotation between, Whitehall Farm, Peterborough (Photo: Stephen Briggs) (Burgess 2017), B. Silvo-pastural paddock grazing for cattle, Peter Aspin Shropshire (Photo: Paul Burgess) (Burgess 2017)

In a review of 28 papers of global agroforestry research Dollinger and Jose (2018) found, enrichment of soil organic carbon better than monocropping systems, improvement of soil nutrient availability and soil fertility and enhanced soil microbial dynamics.

Agroforestry systems are expected to provide an important mechanism for soil protection through reduction of wind erosion in peat soils, (see Figure 1.26A and Figure 1.5) in this example of planting rows of apple trees in a cereal rotation (Burgess 2017). Silvo-arable systems can afford the opportunity to include large numbers of trees in fields whilst still using modern farm machinery to work in cropped alleys between lines of trees (Figure 1.26 B). Silvo-pasture can provide a range of services: shade and browsing for animals, increased biodiversity, carbon sequestration and biofuel in a variety of formats; such as permanent pasture with trees in alleys or between hedges and in field trees (Smith et al. 2021).

8.3 **Converting cropland to long term pasture**

Converting tilled cropland to grazed pasture can drive substantial SOC accumulation (Johnston et al. 2009, Powlson et al. 2011) while providing food and economic return for a landowner (Machmuller et al. 2015). Whilst a permanent land cover may be the best solution for soil function improvement, there is great demand for food from vegetables and combinable crops, such as oats, which require soil tillage and a change of crop.

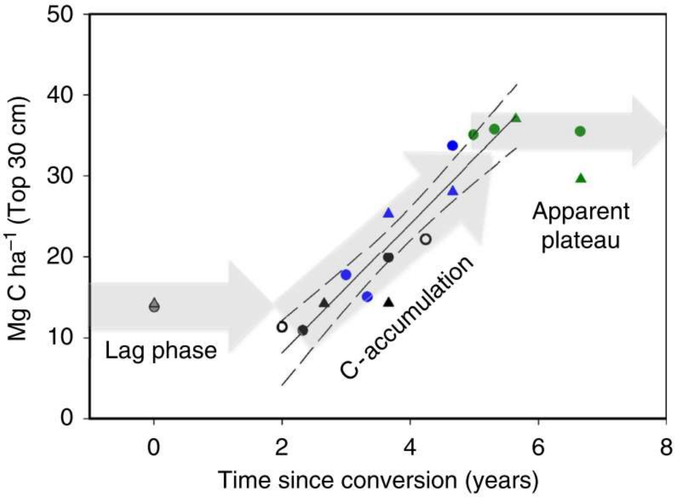


Figure 1.27 Soil carbon rapidly increases with conversion of row crop to intensive grazing (Machmuller et al. 2015)

Soil carbon (MgCha1) content shown for the top 30cm of farms converted in 2006 (green symbols), 2008 (blue symbols) and 2009 (black symbols) and a control farm currently in row crop (grey symbols). Samples from soil pits and soil cores are distinguished by circles and triangles, respectively; open versus closed black circles are from different locations on the 2009 farm. The linear regression (solid line: r^2=0.88, P<0.0001) and 95% confidence intervals (dashed lines) are for data between 2 and 6 years since conversion only. The grey-shaded arrows represent our interpretation of soil carbon change in this system based on current data.

Machmuller et al. (2015) describe their research in a region of extensive soil degradation in the south-eastern United States, they evaluated soil C accumulation for 3 years across a 7-year chronosequence of three farms converted to management-intensive grazing. Figure 1.27 shows that these farms accumulated C at 8 Mg^{-1}ha^{-1}yr-^{1}, increasing cation exchange and water holding capacity by 95% and 34%, respectively. Thus, within a decade of management-intensive grazing practices soil C levels returned to those of native forest soils, and likely decreased fertilizer and irrigation demands. This also draws attention to the long-term nature of the processes involved which many short-term studies may miss. Whilst pasture can be seen as the gold standard for soil regeneration other ways of improving soil are used, such as adding compost or off farm waste products (chicken manure, anaerobic digester digestate and coffee husks are a few examples, see below).

8.4 **Pasture leys and cover crops**

Cultivation of annual crops is desirable to produce cereals, pulses, vegetables and fruits, as these crops generally have a higher protein and calories per unit area, so permanent cropping is not always suitable (Schiere et al. 2002). Other ways can be found of adding carbon to the soil to feed the life that develops the SOM. Carbon can be fixed in situ by growing annual or perennial plants known as leys (Johnston et al. 2017), green manures, catch crops or cover crops (Jahanzad et al. 2016). These can be of different type of plant such as grasses, herbs, legumes or brassicas. Leys are short term pastures which were traditionally used to improve soil health and to produce food for animals in mixed farming systems (often where trees and hedges were also part of the mixed system), described as silvo-pasture above. Leys are usually grown for 2 or more years thus seeing some of the accumulating benefits described by Machmuller et al. (2015), therefore moving the soil part of the way up the C-sequestration curve depending upon length of the ley. Leys can also include legumes and are often grazed, adding nitrogen sources for subsequent crops. Diverse leys also known as herbal leys contain a broader range of species to provide a broader range of ecosystem services (Döring et al. 2013). A cover crop or ley can provide many other and complex ecosystem services (Watson et al. 2002, Schipanski et al. 2014) such as nutrient retention, animal health, AMF colonization and bridge between crops (Kabir and Koide 2002, Trinchera et al. 2019), pest suppression, beneficial insect conservation, soil erosion resistance, soil structure, water services and food for wildlife together with weed suppression for following crops through soil cover, allelopathy, and C sequestration (Poeplau and Don 2015). Trade-offs occur between cover crop ecosystem benefits, production costs, and management risks (Schipanski et al. 2014). Although the decision to sow a cover crop may be driven by a desire to achieve just one of these objectives, the diversity of cover crop species and mixtures available means that there is potential to combine a number of ecosystem services within the same crop and growing season (Storkey 2015).

8.5 **Diverse mixtures of species**

Diverse ley mixtures were used in the UK in the 1930s and 40s before extensive fertiliser applications (Turner 1951). More recently Döring et al. (2013) showed multiply benefits of diverse mixtures: stability of ley performance was greater in multi-species mixtures than in legume monocultures; improvement to soil systems; improvements to yields; mixing different legume species in the ley helped to suppress both early and late weeds; and combining complementary phenologies of different legume species extended forage availability for key pollinator species. Using diverse mixtures means different areas of the soil profile can be accessed by plant roots to activate the whole soil profile and achieve multiple outcomes (the niche differential effect). In simple mixtures of wheat and beans, compared to growing the crops separately, an increase in productivity was found (aboveground overyielding) (Bulson et al. 1997).

Diversity in species (and varieties) leads to community richness giving two clear benefits: **sampling effect** (greater probability that a more productive species will be present); and the **niche differential effect** (better ‘‘coverage’’ of habitat heterogeneity caused by the broader range of species traits in a more diverse community, each species can operate in a different niche avoiding competition)(Tilman 1999). This leads to the proposition that a diverse mixture will likely have the best species and varieties for every spot in a field or on a farm despite the variation in soils and time.

Mueller et al. (2013) found complementary community dynamics with diverse species in a 12-year long-term pasture experiment. In their study diverse species mixtures were found to have rooting twice as deep as would have been expected in monocultures, which also correlated to above ground productivity. Species specific root recognition responses are thought to be responsible for shallower rooting of a four way mixture (Mommer et al. 2010). De Kroon et al. (2012) point out that while there is agreement in the overyielding effects of diverse mixtures the mechanism is disputed due to the previous lack of ability to visually differentiate different species’ coexisting roots. A recent review of 21 data sets was unable to confirm any theory for diverse community root interaction mechanism for aboveground overyielding (Barry et al. 2020).

Lange et al. (2015) show in Figure 1.28, from a long-term grassland experiment, that species richness (plant species diversity) mediates the metabolic activity of soil microbes who govern the storage of soil carbon. This is via higher root inputs of dead material and exudates and other yet undetermined mechanisms. Given that the source and quantity of soil inputs determine the diversity of soil microbial community (Kramer et al. 2012), diverse ley mixtures would lead to diverse soil microbial communities leading to enhanced soil C (McDaniel et al. 2014).

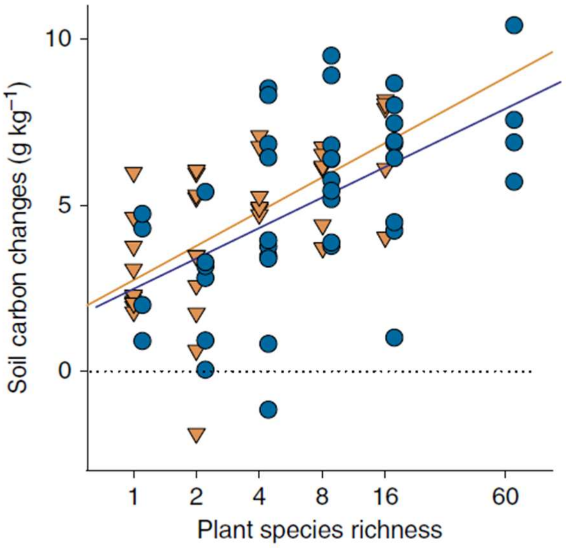


Figure 1.28 The relationship between plant diversity and soil organic carbon storage. Soil carbon changes (g kg_1) between 2002 and 2011 as affected by (log) plant species richness (F1,73=41.29, P<0.001) and the presence (orange triangles) and absence of legumes (blue circles; F1,73=4.37, P=0.040) (Lange et al. 2015)

The interaction of plant roots, soil fauna and soil microorganisms tend to manipulate the soil whilst they are growing, exploring, exuding, dying and decaying in a way that cultivates and tills the soil.

8.6 **Crop rotations**

Crop rotations have been part of mixed farming systems probably for as long as humans have been growing domesticated crops. The temporary fertility building crops mentioned above can be used in rotation with cash crops as already discussed. Temporal diversity to cropping achieved by crop rotation yields some of the benefits of diverse mixtures of species achieved at a single time point, whilst allowing crop segregation to facilitate harvesting and processing of crops. Crop rotations are a traditional method of changing the in-situ crop over time, to rest the soil from nutrient demanding crops, to allow time for animals to graze, to prevent the build-up of pathogens, pests and weeds and to build fertility of the soil. Since the naming of the Norfolk Four Course Rotation in the 17th century (wheat, then turnips, then barley, followed by clover and ryegrass), agricultural science has noted the benefits of crop rotation. The shift here being the removal of the fallow phase from earlier crop rotations (Knox et al. 2011). Both three course and two course systems were common prior to that (Grigg 1974). Rotations or changes in crops can occur during a single year or over several years. The more diverse the rotation the better the services of weed control, pest control and increased yield (Degani et al. 2019). Perhaps of fundamental importance is that crop rotation and plant diversity increase microbial diversity leading to soil aggregation and carbon storage (Lange et al. 2015, Tiemann et al. 2015). Indeed wheat, peas and oats were found to have markedly different rhizosphere microbiomes (Turner et al. 2013) leading to benefits in diversity of rotation. Rotations also serve a similar function to that of moving to new land in shifting cultivation or pastoral nomadism (Spedding 1979). The advent of artificial fertilisers and agrochemicals has replaced some of the functions of crop rotation such as nutrient supply, weed control to cure pest and disease perturbations in conventional farming systems. However, volatility in fertiliser prices, changing and extreme climate, stricter environmental legislation, water pollution (from nitrates, phosphates and agrochemicals) and resistance to agrochemicals by weeds, pests and disease are causing conventional farmers to return to crop rotation as a sustainable remedy (Knox et al. 2011). Whilst it is no panacea it is an important tool especially with future challenges (Bowles et al. 2020) including, reducing carbon emissions, increasing biodiversity, meeting biofuel demands, increased natural fibre production and flood alleviation. These challenges can all benefit from an increased diversity of cropping and perhaps a return to mixed farming akin to historic systems (Knox et al. 2011)

8.7 **Tillage**

Tillage provides several important benefits in cropping systems, which is why it has been so widely used in agriculture (Lal 2009). Tillage removes weeds, provides a seed bed for new plants, aerates the soil, removes competition for new seedlings and mineralises the soil (breaks down soil aggregates to release nutrients making them available to feed plants, see soil aggregation above). At the same time tillage can have detrimental effects, smearing soils forming hard impenetrable surfaces and aiding compaction of soils through the traffic of machinery. The plough, which was historically the enabler of modern agriculture, has evolved to require high horsepower heavy tractors, which emit carbon dioxide both through their combustion engines and through the oxidation of SOM as a result of gross soil disturbance (Lal 2009). Together with the reduction of mixed farming and ley farming systems which might counteract the action of the plough, there has been much focus on changing tillage systems to be less soil damaging. This began in conventional farming in the 1960s and 1970s (Lal 2009). Recently focus has been on the soil carbon impact of reduced tillage methods (Kaiser et al. 2014, Liu et al. 2014), including in alternative farming systems (Moyer 2011, Gadermaier et al. 2012, Mader and Berner 2012) where SOM was seen to increase under reduced tillage together with a positive effect on soil biota (Mader and Berner 2012, Stockdale and Watson 2012, Kuntz et al. 2013). The mechanism for SOM accrual at shallow depths under no-till compared to ploughing can be explained by the breakdown of macroaggregates with vigorous tillage (Six et al. 2000). Various trade-offs suggest that farmers should alternate between conventional and minimum tillage, with frequent additions of OM, to enhance several aspects of soil quality, and reduce disease and yield problems that can occur with continuous minimum tillage (Jackson et al. 2004). There is some debate as to what extent no till methods in conventional agriculture have a positive effect on carbon storage and over what depth of soil (Powlson et al. 2014, Powlson et al. 2015, Smith et al. 2016), following its widespread promotion (Neufeldt et al. 2013) and use in emission trading schemes in the US (Baker et al. 2007). Baker et al. (2007) found that most studies examining the benefits of no-till looked at a maximum soil depth of 30cm, in studies where deeper samples were taken no overall difference in SOC was found between conventional tillage (plough) and no-till as ploughing resulted in greater SOC at depth. Blanco-Canqui and Lal (2008) looked at 11 studies and found that over 0-60cm depth there was no difference in SOC between tillage regimes, but they express strongly that the benefits of water and soil conservation are still important under no-till systems. No-till systems in organic farming are used in the US (Moyer 2011), while reduced tillage systems are preferred to no-till in Europe but are still at an early stage of adoption (Mader and Berner 2012). A study by Gadermaier et al. (2012) concluded that reduced tillage with diverse ley based organic farming systems merits further promotion.

With regards to concerns about weed control with non inversion tillage, it should be possible to develop high density cereals that can utilize their initial size advantage over weeds to suppress them much better than under current practices, thus reducing or eliminating the need for chemical or mechanical weed control (Weiner et al. 2010). Indeed Mertens (2002) found that crops planted in narrow rows produced fewer weed numbers than crops planted in wide rows with interrow hoeing. Taking this one step further, planting seeds in a network arrangement, where each seed is equidistant from its neighbours, reduces weed burden further (Olsen et al. 2005), eliminating the need for post-sowing tillage for weed control.

8.8 **Animals as part of a dynamic ley system**

Integration of livestock into cropping systems can have many benefits: weed control, increased SOM as described above, addition of farmyard manure, spreading of soil biota by animal hooves and manure when grazing and the addition of leys to a rotation (see next section) (Reeder and Schuman 2002, Riches 2003). Long-term organic farming and the application of farmyard manure increased the resource basis for belowground communities and beneficially affected the activity and biomass of decomposer biota (Birkhofer et al. 2008). A comprehensive study indicates that organic fertilizers, as part of a mixed farming system, foster biotic interactions within and between below and aboveground components thereby improving the sustainability of farming systems (Birkhofer et al. 2008). The benefits of diverse ley farming systems have been explained above and can be exploited economically through their consumption by livestock, both ruminant and monogastric livestock, whilst the diverse leys are growing and building their fertility and soil function in agroecosystems (Baker et al. 1990). In a Swedish study the limiting of livestock production to pasture, rather than feeding cereals or concentrates, had positive impacts for the environment and food security (Röös et al. 2016).

8.9 **Adding or importing organic matter**

Organic matter (OM) can be imported to a cropping system as compost, green waste, wood chip or other plant products (Diacono and Montemurro 2011). In an experiment of intensive vegetable production on differing tillage and OM additions, addition of cover crops and compost increased microbial biomass carbon (MBC) and nitrogen (MBN), reduced bulk density, and decreased the NO3-N pools in the 0–90cm profile, so that leaching potential was lower compared to plots without OM treatments (Jackson et al. 2004). Long term (3-60 years) organic amendments have been found to have positive effects on microbial biomass, soil carbon, aggregate stability, bulk density and crop yield, though toxic elements may accumulate (Abiven et al. 2009, Diacono and Montemurro 2010, Kallenbach and Grandy 2011, Kätterer et al. 2014, Xie et al. 2015). A 7-year study of repeated additions found total SOC increased by an average of 3% for every 10 t/ha manure applied, organic carbon (OC) and light fraction OC (LFOC) increased by around 14% (Bhogal et al. 2009), they also found the manure OC inputs (but not crop residue OC inputs) increased topsoil porosity and plant available water capacity, and decreased bulk density by 0.6%, 2.5% and 0.5% with every 10 t/ha manure OC applied, respectively. Another study found no increase in SOM with increasing soil C inputs (Chung et al. 2010) which is consistent with the theory of SOM saturation and saturation deficit discussed in section 3 above. The quality of imported (or retained) organic matter will clearly affect the soil health outcomes (Bhogal et al. 2009, Diacono and Montemurro 2010).

8.10 **Organic farming**

"…Various organic technologies have been utilized for about 6000 years to make agriculture sustainable while conserving soil, water, energy, and biological resources. Among the benefits of organic technologies are higher soil organic matter and nitrogen, lower fossil energy inputs, yields similar to those of conventional systems, and conservation of soil moisture and water resources (especially advantageous under drought conditions). Conventional agriculture can be made more sustainable and ecologically sound by adopting some traditional organic farming technologies…" (Pimentel et al. 2005). Organically grown food is recognised in law and is thereby able to achieve a separate demand to other production methods.

Due to the adverse effects of agrochemicals, organic farming that relies on organic amendments for plant nutrition and natural products for protection from plant pathogens and pests, has been proposed as an environmentally friendly, low intensive cultivation approach (Reganold and Wachter 2016). Long-term organic farming and the application of farmyard manure promotes soil quality, microbial biomass and fostered natural pest enemies and ecosystem engineers, suggesting enhanced nutrient cycling and pest resilience (Birkhofer et al. 2008). Their study, suggests improved soil quality and a higher resilience to pests in organic systems compared to systems receiving mineral fertilizers and pesticides, in particular to the system receiving only mineral nutrients (Birkhofer et al. 2008). Many studies have shown the beneficial effects of organic cropping systems compared to chemical cropping systems, on soil biota (Mader et al. 2002, Bonanomi et al. 2016, Hendgen et al. 2018). Sugiyama et al. (2010) showed a slightly higher diversity and evenness within the microbial community on organic farms compared with conventional farms.

However, organically produced crops can have lower yields per unit area than conventional crops (de Ponti et al. 2012, Seufert et al. 2012, Röös et al. 2018). Addressing this yield gap is of urgent concern if the other positive attributes of organic farming are not to be ignored (Smith et al. 2019). Soil fertility improvement is the primary focus for increasing yields in organic systems particularly by increasing organic matter (Watson et al. 2002).

Hepperly (2009) suggests quantities of synthetic chemical fertilization inputs tend to be static or increase over time. Whereas requirements of organic compost for crop nutrition tend to decrease due to the slow, persistent release of nutrients from composted materials and to the build-up of stable soil nutrient reserves. Soil fertility input needs are reduced as nutrients are bound and cycled within the soil. Use of synthetic chemical fertilizer tends to reverse this stable nutrient cycle as more soluble N inputs enhance the breakdown of soil organic matter, depleting the native soil fertility processes that are invested in soil organic material. Based on the loss of soil C and N and soil acidification, chemical fertilizer can be expected to lead to increased dependence on greater chemical inputs over time, while compost use helps to build a more self-sustaining soil nutrient cycle that provides a wide range of nutrients for healthy plant growth (Hepperly 2009). Some widely used organic principles have been adopted by conventional cropping systems to address some of the growing challenges such as pesticide resistant weeds. This is called integrated weed and pest management IWM/IPM (Swanton and Murphy 1996).

In 2015, about 44 million hectares worldwide were managed organically and about 12 million in the European Union (Willer and Lernoud 2016). Yatesbury House Farm began its conversion to organic farming in 1998, following empirical assessments of many organic farms, an increasing awareness of the dangers that pesticides pose to farm operators and the deteriorating quality of the farm soil under the conventional farming system. At Yatesbury the shift away from natural processes towards a controlled and cure-based system was leaving a vulnerable system rather than an inherently resilient system.

Conclusion/knowledge gaps

The importance of the soil has gained much traction at every level over the duration of this study. The state of global soils has become more widely understood and the impact of soil degradation to agriculture and biodiversity more recognised. However, it is the potential that soil holds in the global climate crisis for both change mitigation and adaptation that makes this subject pertinent and attract a wider audience.

This literature review has looked at the edaphic mechanisms for improving soil health and the cropping systems that facilitate these mechanisms.

There are limited studies that look at the soil impacts of adding biomass over a longer temporal scale. Temporal scale is particularly important when looking at changes in the soil as these changes can take many years to realise.

There are many papers discussing the need for carbon sequestration, with government and global targets set to achieve more soil carbon storage aiming for greater soil health whilst remove carbon dioxide from the atmosphere. The research on how to achieve this is sometimes conflicting. There is therefore a gap in knowledge and pressing need for research into how to sequester more carbon in soils with modern cropping systems. This experiment seeks to help address the question: can agroecological systems store more soil carbon, so that agriculture can contribute to addressing both climate change mitigation and adaptation?

There are gaps in knowledge regarding the question of the economic value of feeding the soil with plant material (biomass) produced in-situ, both short and long term. As farming has become more efficient there has been less by-product returned to the soil to feed the soil biology, efficiency and the short-term profit motive have disregarded any need to feed the soil life as the services provided by the soil organisms were generally unrecognised or replaced by artificial means which were more short-term cost effective. This research aims to fill that gap in understanding of the economic value assigned to soil regeneration in terms of crop productivity. Also, to assess the effects that feeding the soil has on soil function, soil biota characteristics and crop effects.

Whilst organic farming systems are recognised for their many beneficial traits the yield gap between organic and conventional yields, in some temperate climate crops, restricts further uptake of organic farming systems. Addressing this yield gap is therefore of urgent concern.

The literature review shows that there is a good deal of scientific papers that support the farming systems used in the experiment in the context of soil regeneration. By carrying out the experiment on farm with farm machinery this also highlights the accessibility of the scientific method to all cropping farms.

Structure of Experiment and Discussion chapters

The experiment has been carried out on-farm at Yatesbury to investigate the impacts of retaining crop residues in a crop rotation with 2 years diverse ley, compared to removing this crop residue biomass. Comparison was also made to two extreme reference treatments in this context, a positive control of 5 years diverse ley and a negative control which was routinely tilled for 5 years to remove plant growth. The structure of the chapters is directed to follow the potential impact of the biomass input. The first area or order of impact is likely to be in the soil organic matter implying changes to the soil physical properties; second order effects, from feeding the soil, are the impact on the soil biota, particularly the soil fauna who consume the fresh plant litter transforming it into plant food (soil organism faeces) and soil organisation through the biota activity; third order effects are the outcomes in the crops growing in the soil with the different treatments. There will be some repetition in Chapters 2 to 4 as this thesis is written as chapter-papers.

Chapter 2 First order soil characteristics

Chapter 2 looks at first order soil characteristics and asks if adding biomass to the soil increases soil organic matter, soil labile carbon and soil function in terms of soil water infiltration rates and physical structure.

Hypotheses and tests:

1. Adding biomass increases SOM at 0-100 mm depth: Tested by organic matter loss on ignition.
2. Adding biomass increases SOM at depth (100-300 mm): Tested by OM loss on ignition.

3. Adding biomass increases labile carbon as an indication of soil health improvement: Tested using labile carbon assessment.
4. Adding biomass improves soil water holding capacity: Tested by water infiltration rate and bulk density at three depths.
5. Adding biomass lowers soil compaction at various depths: Tested by bulk density and penetrometer point pressure.

Changes will be considered a) relative to the standard treatment, b) the carbon input references, and c) relative to the baseline established at the start of the experiment in each plot.

Chapter 3 Soil biota

Chapter 3 assesses the soil biota characteristics (second order effects) of adding biomass. Are soil flora and fauna activities improving soil water and physical properties in terms of increased aggregation of soil (are the activity of plant roots and soil organisms improving soil function)? Does weed burden change with additions of biomass?

Hypotheses and tests:

1. Adding biomass increases soil meso fauna numbers: Tested by using a Tullgren funnel; also known as Berlese trap.
2. Adding biomass increases soil aggregate stability to rapid wetting: Tested by the Slake test.
3. Adding biomass reduces weed burden: Tested by measuring weed numbers and weed biomass.
4. Adding biomass reduces fungal burden: Tested by measuring crop senescence rate.

Chapter 4 Crop value

Chapter 4 assesses the third order impact in crop value. It looks at the yield and quality of the crops grown in the treatment plots and asks if there are financial benefits to subsequent crops from returning biomass to the soil rather than selling it off farm?

Hypotheses and tests:

1. Retaining crop residues increases crop yield and reduces variability in yield: Tested by combine yield by hand and crop establishment counts.
2. Retaining crop residues increases crop quality: Tested by grain characteristics including hectolitre weight, and forage quality brix test.

Chapter 5 General discussion, feeding the soil to benefit soil and farm homeostasis

- Discusses the proposition that feeding the soil biota can be viewed as an insurance policy
- Discusses the ways of engaging with farmers in facing the coming change
- Demonstrates to farmers a robust way of carrying out on farm experimentation that is easy to operate with the farm's existing farm machinery and produces positive outputs that farmers can share with their colleagues.
- Summarises the recommendations for changes to whole farm systems and cropping systems following the experimental chapter conclusions.

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Chapter 2. First Order Soil Characteristics

Introduction

Carbon Capture is a critical concept in mitigating climate change, which reduces atmospheric greenhouse gas concentration increased by anthropogenic activities (Fawzy et al. 2020). Carbon sequestration in the organic matter of agricultural soils is a relatively low cost technique of carbon capture with multiple additional benefits (Bossio et al. 2020). Increases in soil organic matter (SOM) within crop rotations have been linked with increases in below-ground and above-ground biodiversity (Thiele-Bruhn et al. 2012, McDaniel et al. 2014), crop productivity (Lange et al. 2015) and flood and drought resilience (Falkenmark and Rockström 2008). Carbon capture in agricultural soils is both a climate change mitigation and adaptation strategy.

The fact that the soil stock has been degraded across the world is not news (Lal and Stewart 1992). To date humanity has released about 116 Pg of soil carbon (C) into the atmosphere globally (Sanderman et al. 2017). Land use change and over-exploitative farming practices have exposed the soil to erosion (Montgomery 2007), impacted above ground biodiversity (Gilroy et al. 2008) and steadily degraded the global soil resource as a result.

A healthy soil is typical for high or increasing SOM (Loveland and Webb 2003), which is clearly beneficial for crop production and society (Acton 1995, Dwyer et al. 2015). Soil health is commonly defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (Lehmann et al. 2020). Healthy soils feature soil structure and aeration, nutrient cycling and provision, salinisation prevention, soil-borne plant pathogen suppression, and the diversity of soil flora and fauna population: all characteristics supportive of crop growth (Janvier et al. 2007, Senechkin et al. 2014, van Bruggen 2015). SOM is one of the key soil components that underpins these functions (Lehmann and Kleber 2015). The management of SOM in agricultural soils is a dynamic process that requires continuous input of fresh organic material, otherwise the level of SOM decreases (Montgomery 2007). The understanding of the direction and the speed of SOM change is critical to solving soil degradation problems (Loveland and Webb 2003) and must be at the forefront of our effort to combat climate change (Montanarella and Panagos 2021).

Carbon capture in SOM in productive systems will be determined by achievable carbon accumulation rate and limited by the capacity of soil to store carbon, with absolute levels of SOM being critical. The global carbon storage potential in the soil is 114-242 Pg C (Lal et al. 2018), equivalent to more than a decade of human carbon emissions at current rates (Amundson and Biardeau 2018). Agricultural land management systems influence both the mechanisms controlling SOM accumulation rate and the degree of saturation (Six et al. 2002). Currently, the main challenge in any soil regeneration intervention is time, the benefits are likely to accrue over long-time horizons and stay below the detection threshold for some time (Johnston et al. 2009, Machmuller et al. 2015).

Improving carbon storage in soils represents a challenge for land managers to introduce disruptive techniques that build soil organic matter in annual cropping systems (Minasny et al. 2017). For example, partial or complete reductions in tillage have been trialled but with limited success (Powlson et al. 2014, Blanco-Canqui and Wortmann 2020). Blanco-Canqui and Lal (2008) looked at 11 studies and found that over 0-60cm depth there was no difference in SOM as a result of changing tillage regimes. Clearly, theoretical understanding of SOM dynamics indicates that increased carbon storage is possible, but the limitations of real-world productive systems are slowing down progress.

Land use change from annual cropping to long-term pastures is known to accumulate SOM (Machmuller et al. 2015). However, there is great demand for annual crops such as vegetables, pulses and cereals (Tilman et al. 2011). A short-term ley as part of a crop rotation can provide a degree of these perennial crop benefits (Powlson et al. 2011, Poulton et al. 2018) whilst still facilitating the demand for annual crops. The ley’s main purpose is soil protection and improvement, however they can also directly contribute to profitability and their diversity can stabilise farm income (Harkness et al. 2021). The strategic use of fertility building leys can strongly reduce the dependence on imported nutrients (Thorup-Kristensen et al. 2012). External inputs represent potentially high risk solutions beyond the control of the farmer, subject to trade and market fluctuations (highlighted by the Covid-19 disruption) or resulting in increased N leaching and pest infestations (Röös et al. 2018).

Plant species diversity can enhance the impact of leys on soil health and crop yields (Döring et al. 2013, Lange et al. 2015). Highly diverse leys root twice as deep as expected from their monoculture traits, giving access to greater soil resource which can correlate with aboveground productivity (Mueller et al. 2013). Plant species diversity mediates the metabolic activity of soil microbes that governs the storage of soil carbon (Lange et al. 2015). This process is thought to be driven by changes in root biomass quantity and quality, root exudation, symbiosis support, and perhaps other currently unknown mechanisms (Lange et al. 2015). Diverse plant species communities lead to diverse soil microbial communities, and result in enhanced soil C (McDaniel et al. 2014). Soil regeneration thus implies biodiversity regeneration in agricultural landscapes (Gilroy et al. 2008) and belowground biodiversity gains lead to increased crop yield (Lange et al. 2015).

There are many studies impressing the need for carbon sequestration and improved soil health, but the approaches tried have met with varying degrees of success. The methods for sequestering carbon whilst continuing to produce annual crops exist but have been slow to hit the mainstream. Whilst there is limited research into diverse mixed species of ley in crop rotation systems, there is a gap in knowledge as to their impact on soil characteristics and function, in particular change in SOM.

This study explores the use of plant biomass, primarily created by a diverse ley of 23 species, to drive soil function regeneration through SOM accumulation - within a working farm context. The change in soil organic matter was explored across four fields in an organic, diverse ley, crop rotation from 2014 to 2019, using a space for time arrangement to capture the entirety of the 7-year rotation practiced on this farm. Retaining crop residues (enhanced treatment) was compared to their removal (standard treatment) in a diverse ley rotation featuring 2-year ley phase, and to a 5-year ley phase (positive reference) and a routinely tilled fallow treatment-plot (negative reference). All treatments represent realistic interventions practiced by farmers; the study is constrained within the confines of an economically viable working system. An existing rotation was used to explore how varying the level of organic matter inputs impacts soil health. Five testable hypotheses were investigated:

1. Adding biomass increases SOM at 0-100 mm depth, tested by organic matter loss on ignition.
2. Adding biomass increases SOM at depth (100-300 mm), tested by OM loss on ignition.
3. Adding biomass increases labile carbon as an indication of soil health improvement, tested using labile carbon assessment.
4. Adding biomass improves soil water holding capacity, tested by water infiltration rate and bulk density at three depths.
5. Adding biomass lowers soil compaction at various depths, tested by bulk density and penetrometer point pressure.

Changes will be considered a) relative to the standard treatment, b) the carbon input references, and c) relative to the baseline established at the start of the experiment in each plot.

Chapter 2

Methodology

Site description

The experiment was set up at Yatesbury Farm, at the Western edge of the Marlborough Downs, in the South of England (51°26’32.68”N, 1°54’08.57”W). The geology is lower grey chalk, the upper soil texture being silty clay loam (Blewbury and Yatesbury soil series) (Findlay and Colborne 1984). Most of the land has less than 1° incline, daily average temperature ranges from -2 °C to 24 °C (2016-2019), mean annual rainfall is 662.25 mm (2016-2019, weather data supplied by Iteris). The farm comprises 550 hectares of cropping, pasture and woodland together with a 280 head suckler herd. Organic conversion began in 1998, having previously been farmed in intensive arable production in the 1990s, the farm is also managed biodynamically (Mader et al. 2002, Birkhofer et al. 2008). The farm has not been ploughed since 2003, light/reduced tillage to approximately 75mm is used instead.

Experimental design

Four fields were chosen to represent the rotation typical for the farm (detailed below) on a space for time substitution basis (Pickett 1989) and to best represent the soil and weed diversity across the farm. Each of the four fields had a research area 80 m x 78 m demarcated away from field margins, comprising three replicate blocks of experimental plots (Figure 2.1). Each replicate block contained four treatment-plots (Figure 2.1) where the treatments described in Table 2.1 were applied continuously. Cattle were excluded from the research areas.

Figure 2.1 (a) Aerial Map of experimental field locations (orange squares) (b) drone image of Croft field showing plots within field setting (c) drone image of the layout of 3 replicate blocks of 4 treatment-plots (full-size-plots: size 8 m x 80 m) within a single field (Croft Field). Treatments: Negative reference (1); Positive reference (2); Standard (3); Enhanced (4), (the 2 reference treatments share one full-size-plot)

Table 2.1 Experimental treatments as replicated throughout the experiment, enhanced and standard represent normal crop rotation, references are two boundary soil treatments

Name	Treatment
Positive reference treatment	Continuous diverse ley representing max carbon input with retention of all crops
Enhanced input	In-field retention of crop residues and cultivation of Winter cover crops
Standard input	Crop residues are removed
Negative reference treatment	No crop, routine tillage at 3 times yr^{-1}: Spring, Summer and Autumn, to restrict plant growth

All treatments were randomly allocated to individual treatment-plots within a block, reference treatments were allocated half size plot as no crop measurements were carried out within these. The standard treatment represents the business-as-usual scenario in this region, where crop residues are removed and sold off-farm. The enhanced treatment represents in-field retention of crop residues or Winter cover crops. The crop and management within each field is shown in Table 2.2.

Table 2.2 Crop rotation and the position of individual fields within the rotation at the beginning of the experiment in 2014. Two RH columns indicate main crop management interventions during each year of rotation.

Rotation Year	Rotation Crop	Field in 2014	Standard Biomass-Input Treatment	Enhanced Biomass-Input Treatment
1	Diverse ley	Long Barrow	Mowed for hay/silage	Topped after 15th June to promote lignin production and reduce weed seed set
2	Diverse Ley		Grazed	Grazed
3	Cereal: Spelt or Wheat or Oats	Hut Field	Remove straw	Chop & incorporate straw
4	Cereal: Spelt or Oats		Remove straw	Chop & incorporate straw
5	Bean whole crop silage	Fifty Acres	Harvested as forage silage	Cut and mulched as green manure nothing harvested
6	Spring Beans		Fallow over winter	Green cover over winter
7	Spring Oats under sown with diverse ley	Croft Field	Harvest as whole crop	Chop & spread straw and green material

Weather, commodity market, weed burden and changing fertility have encouraged variations to crop interventions over the period of the experiment according to common farming practice. Crop management in the enhanced plots focussed on adding as much biomass from in-situ plant growth as possible to the soil. The quality of the biomass varied according to the crop grown and the season and was not measured. A diverse mixture of 23 ley species was used to maximize the performance of the key ley phase (Döring et al. 2013).

Field sampling protocols and laboratory analysis

The location of plot sampling sites was determined by using a stratified random approach by first splitting each full-size-plot into quarters, then either using the soil core location as described below or randomly generating coordinates for one sampling site per quarter. This resulted in 4 sampling sites per full-size-plot (2 sampling sites per reference plots), 36 per field, 144 across all four fields of the experiment.

Soil baseline cores were taken in Autumn 2014 throughout the plots, the samples were taken 0.5 m in from the start of each quarter plot and along the centre line of the plots (Figure 2.1). The cores were taken at 0-100 mm and 100-300 mm depth, diameter 80 mm and stored at -20 ^{O}C until analysis. A second set of soil cores was taken in Autumn 2019 according to the same sampling design, 2 m in from the start of the quarter plots. In November 2019, the 2014 cores were defrosted, and all cores were analysed by NRM laboratories (Bracknell, UK) for SOM, phosphorus (P), potassium (K), magnesium (Mg), pH and labile carbon. SOM was analysed using loss on ignition (LOI) (NRM 2019). These samples were first air-dried at a temperature not greater than 30 ^{O}C and sieved to 2 mm, the organic matter was then destroyed by dry combustion at 430 ^{O}C and the loss in weight of the sample is reported in g/kg of the original sample as the organic matter content. Soil organic carbon (SOC) was not directly measured in this experiment, historically a conversion factor of 0.58 has been used to transfer SOM measures to SOC (Pribyl 2010). However, several studies have suggested this factor is not always accurate and will vary depending upon the age of the organic matter and the method of SOM analysis used (for LOI this includes the furnace temperature), (Pribyl 2010, Hoogsteen et al. 2015, Roper et al. 2019). SOC has not been estimated, rather relative change over time in SOM was taken which will be the same relative change over time for SOC. Considering a relative change helps to eliminate potential errors in both baseline and end-state SOM estimates, such as due to clay bound water and $CaCO_3$, the same error is likely to occur in both estimates. The pH was measured potentiometrically, phosphorous was measured by Olsen's extraction method (Olsen 1954) and ammonium nitrate extraction method was used to determine extractable potassium and magnesium (Rowell 1994). Labile carbon was assessed by reacting potassium permanganate ($KMnO_4$) solution with soil samples and determined by spectroscopy (Weil et al. 2003, Schindelbeck 2016).

Bulk density samples were taken in September 2018 following the centre line approach above, at 5m start point, using a spade and digging a hole to a depth of 500 mm with enough clearance to hammer in the cylinder horizontally. Bulk density samples were taken using the metal ring of a known volume at 3 depths: 0-100 mm; 100-300 mm and 300-500 mm using the USDA standard bulk density protocol (USDA 2020).

Water infiltration rates were assessed by filling a 150 mm diameter tube with water. The tube was driven 7.5 cm into the soil, 444 ml of water (equivalent to 25 mm of precipitation) were added into the tube to simulate field capacity, then a second batch was added and the time for the water to percolate into the soil was measured.

Manual penetrometer (Utset and Cid 2001) readings were taken at randomly determined points within each plot by pushing the penetrometer into the soil at a uniform speed and recording the point pressure at each depth at a range of 100 mm-700 mm. The penetrometer sizes were probe length: 75 cm; probe diameter: 12 mm; tip diameter 13 mm. All soil compaction measurements were taken in years 2017, 2018 and 2019.

Statistical analysis

Data was recorded and validated for completeness, change in SOM from 2014 to 2019 was calculated as a derived variable (SOM2019-SOM2014). Measurements taken at four sampling sites within the enhanced and standard treatments and at two sampling sites in each reference treatment, they were analysed using a nested mixed model with treatment-plot nested in replicate and replicate nested in field (1|field/replicate/treatment-plot). Field, replicate and treatment-plot terms were treated as random effects. Mixed models were used to analyse all the responses, with a support distribution as required by each outcome, namely: Normal or Lognormal.

The 2014 baseline observations of SOM, pH, P, K, Mg and labile carbon were compared with the 2019 data to assess the change. A Summary Statistics Approach for the years of repeated measures was used. A Normal distribution used to model SOM change, adding baseline covariates to the model was tried but it didn’t improve model performance so they were dropped, a Lognormal distribution could not be used as some values were negative. A normal distribution was used to model labile carbon in 2014 and 2019. Labile carbon varies with season and year depending upon growing conditions (Jiang et al. 2006, Kirschbaum 2013), so no direct comparison between 2014 and 2019 was made. A Normal distribution was used to model bulk density by treatment. A

Lognormal distribution was used to model infiltration by crop and treatment due to large, tailed data. A Normal distribution was used to model penetrometer readings at 100mm and 200m depth. In interpreting the results some statistically significant results may be of such small effect to be of no practical importance, these are noted. The data was analysed and modelled in R, version 4.1.0. The denominator degrees of freedom were in all cases computed by the Kenward-Roger method. P-values of less than 0.05 are deemed indicative of statistically significant effects.

Results

Soil Organic Matter

Initial soil cores were taken in 2014 at the start of the experiment and then in 2019 at the end, to measure SOM. 2014 soil cores were frozen and tested together with 2019 cores to ensure direct comparative results. Figure 2.2 shows SOM for each treatment at each depth giving an indication of the direction of change in SOM over the experimental period.

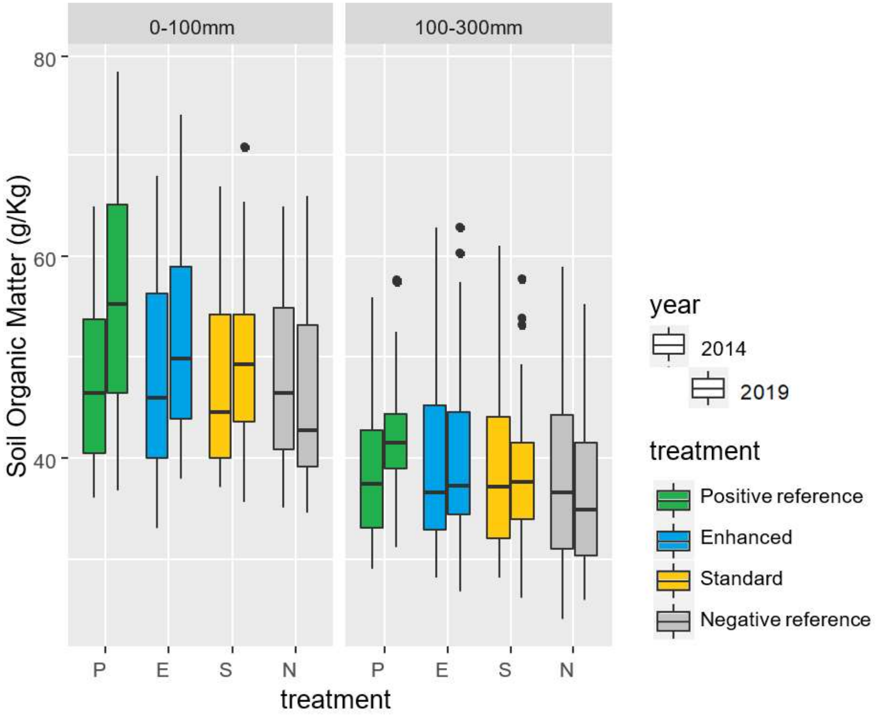

Figure 2.2 Soil Organic Matter (g.kg^{-1}), by treatment, soil depth and year (in pairs: left 2014; right 2019), measured using the loss on ignition method. Boxplots indicate medians, interquartile ranges and extreme values beyond 95%.

SOM changed over 5 years in this experiment at both 0-100 mm and at 100-300 mm depths (overall treatment effect $p<0.001$). The largest change in SOM occurred in the positive reference (5-year ley), with an increase of 8.2 $g.kg^{-1}$ SOM over 5 years (CI 6.0 to 10.5, $p<0.001$) at 0-100mm depth and 3.0 $g.kg^{-1}$ SOM (CI 0.7 to 5.2, $p=0.013$) at the 100-300 mm depth (Table 2.3). Both the enhanced and standard treatments increased SOM at the 0-100 mm depth (3.7 $g.kg^{-1}$ (CI 1.7 to 5.6, $p<0.001$), 2.8 $g.kg^{-1}$ (Cl 0.9 to 4.8, $p=0.008$), respectively).

Table 2.3 Change in SOM content ($g.kg^{-1}$), between 2014 and 2019, predicted means by treatment and depth, with 95% confidence intervals and p-values representing probability predicted mean change in SOM is zero (H_o)

treatment	emmean	lower CI	upper CI	p-value
				depth = 0-100mm:
Positive reference	8.223	5.948	10.497	<0.001
Enhanced	3.666	1.707	5.625	0.001
Standard	2.826	0.867	4.784	0.008
Negative reference	-0.583	-2.858	1.692	0.606
				depth = 100-300mm:
Positive reference	2.951	0.676	5.226	0.013
Enhanced	0.3	-1.659	2.259	0.750
Standard	-0.289	-2.248	1.67	0.758
Negative reference	-1.44	-3.715	0.835	0.207

The enhanced treatment was not different to the standard treatment at either depth (Table 2.4, Appendix Figure 2.8). The positive reference was greater than all the other treatments and the negative reference was lower than all the other treatments at 0-100 mm, at the 100-300 mm depth only the positive and negative references were different (Table 2.4).

Table 2.4 Change in SOM content ($g.kg^{-1}$), between 2014 to 2019, contrast of treatment pairs at the two depths, 95% confidence intervals

Contrast of treatment pairs	estimate	lower CI	upper CI	p-value
				depth = 0-100mm:
Positive reference - Enhanced	4.56	1.19	7.93	0.004
Positive reference - Standard	5.40	2.03	8.77	<0.001
Positive reference - Negative r.	8.81	5.07	2.54	<0.001
Enhanced - Standard	0.84	-2.13	3.82	0.88
Enhanced - Negative reference	4.25	0.88	7.62	0.008
Standard - Negative reference	3.41	0.04	6.78	0.046
				depth = 100-300mm:
Positive reference - Enhanced	2.65	-0.72	6.02	0.174
Positive reference - Standard	3.24	-0.13	6.61	0.064

Contrast of treatment pairs	estimate	lower CI	upper CI	p-value
Positive reference - Negative r.	4.39	0.66	8.12	0.014
Enhanced - Standard	0.59	-2.39	3.56	0.952
Enhanced - Negative reference	1.74	-1.63	5.11	0.532
Standard - Negative reference	1.15	-2.22	4.52	0.807

Comparison of SOM content between 2014 and 2019 in Figure 2.3 shows an effect of treatment on rate of SOM accumulation (p=0.024). Within the observed range, the positive reference added carbon at a constant rate irrespective of initial level of SOM. The enhanced and the standard treatments added SOM at a progressively diminishing rate. The regression lines in these two treatments cross the one-to-one line at approximately 67.5 g.kg^{-1} SOM, indicating a possible SOM plateau under current management practice. The negative reference regression fit also indicates saturation, while the maximum SOM content under the positive reference treatment is beyond the observed range of the experiment.

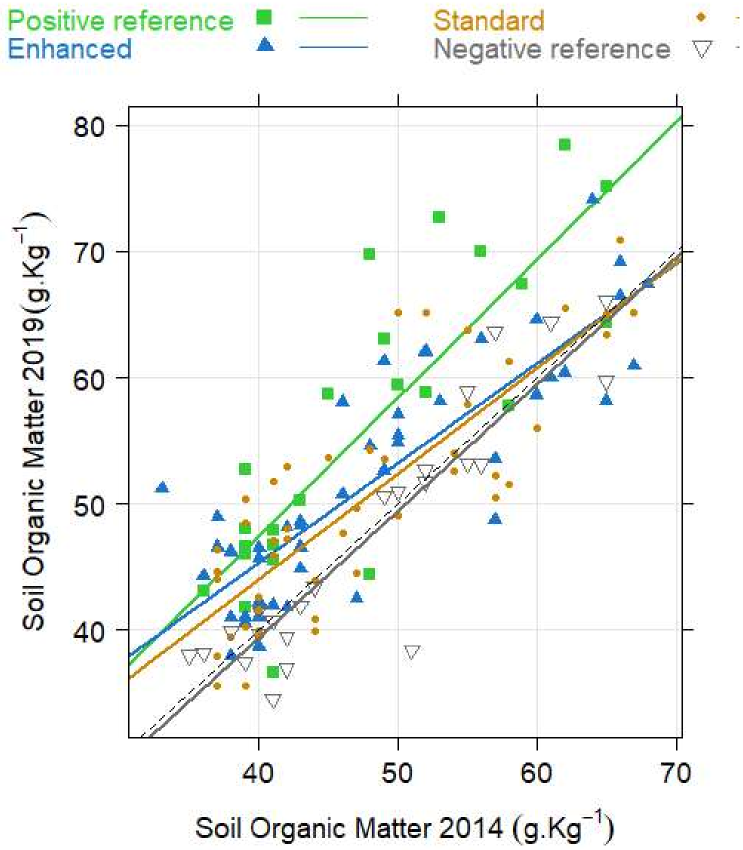

Figure 2.3 Scatterplot of SOM 2014 against SOM 2019 at 0-100 mm soil depth with linear regression lines. Experimental treatments refer to positive reference (green squares and line), enhanced (blue triangles and line) and standard (gold circles and line) and negative reference (grey diamonds and line). The dashed line represents the one-to-one line.

The predicted annual relative percentage change in SOM was calculated and is shown in Appendix Table 2.9. At the 0-100mm depth, the positive reference gave a 3.15% yr^{-1} relative increase in SOM from 2014 to 2019 (CI 2.12 to 4.18, $p<0.001$), enhanced treatment a 1.59% yr^{-1} increase (CI 0.69 to 2.51, p=0.003) and standard treatment a 1.21% yr^{-1} increase (CI 0.30 to 2.12, p=0.014). At the 100-300 depth the positive reference gave an annual relative increase in SOM from 2014 to 2019 (estimate=1.57, CI 0.06 to 3.09, p=0.044), with no change for the other treatments.

Labile Carbon

Data from the core measurements of 2014 and 2019 were tested for labile carbon, the results are shown in Figure 2.4.

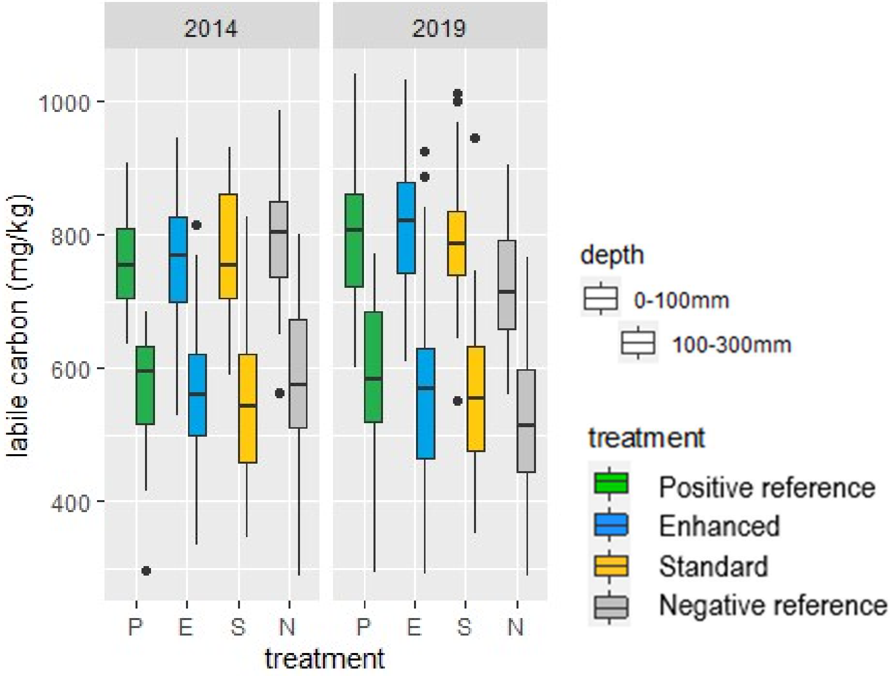

Figure 2.4 Labile carbon ($mg.kg^{-1}$), in 2014 and 2019 by treatment, by year and by depth (in pairs: left 0-100 mm; right 100-300 mm), Boxplots indicate medians, interquartile ranges and extreme values beyond 95%

As mentioned previously, labile carbon varies with season and year depending upon growing conditions (Jiang et al. 2006, Kirschbaum 2013), so no direct comparison between 2014 and 2019 was made. In 2019 at the 0-100 mm depth there was an overall treatment effect (p=0.002) but not at the 100-300 mm depth (p=0.107). Predicted means are shown in Table 2.5 and Appendix Figure 2.9.

Table 2.5 Labile carbon (mg.kg^{-1}) in 2019, predicted means 95% confidence intervals, by treatment and depth

treatment	emmean	lower CI	upper CI
			depth = 0-100 mm
Positive reference	799	739	858
Enhanced	817	758	876
Standard	787	727	846
Negative reference	724	665	784
			depth = 100-300 mm
Positive reference	590	515	666
Enhanced	559	484	635
Standard	562	486	637
Negative reference	517	442	593

Compared to the negative reference, labile carbon in 2019 was greater under all other biomass treatments at the 0-100 mm depth (positive reference, enhanced and standard) (Table 2.6). There was no difference between the positive reference, standard and enhanced treatments.

Table 2.6 Labile carbon (mg.kg^{-1}) in 2019, contrasts of treatment pairs of Labile carbon 95% confidence intervals

contrast	estimate	lower CI	upper CI	p-value
				depth = 0-100mm:
Positive reference - Enhanced	-18.4	-78.16	41.4	0.842
Positive reference - Standard	11.7	-48.14	71.5	0.953
Positive reference - Negative r.	74.2	9.22	139.1	0.019
Enhanced - Standard	30	-24.62	84.7	0.441
Enhanced - Negative reference	92.5	32.72	152.3	0.001
Standard - Negative reference	62.5	2.7	122.3	0.038
				depth = 100-300mm:
Positive reference - Enhanced	30.75	-39.33	100.8	0.643
Positive reference - Standard	28.56	-41.51	98.6	0.694
Positive reference - Negative r.	73.12	-3.41	149.7	0.066
Enhanced - Standard	-2.19	-65.77	61.4	0.999
Enhanced - Negative reference	42.38	-27.7	112.5	0.377
Standard - Negative reference	44.56	-25.51	114.6	0.333

Bulk Density

The data gained from the 2018 bulk density analysis of the treatments and references is shown in Figure 2.5.

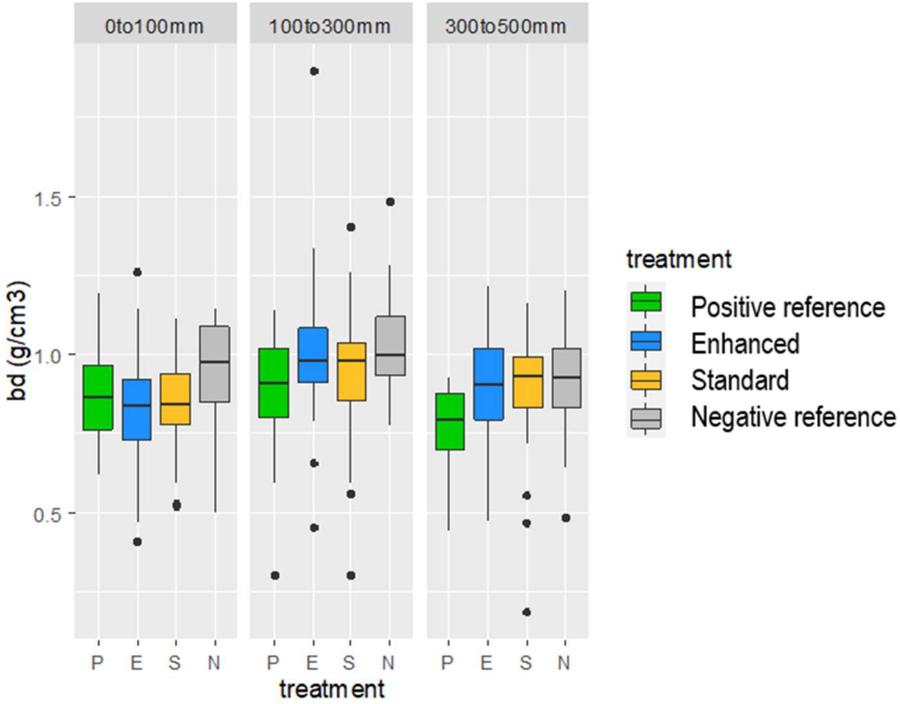

Figure 2.5 Bulk density (g.cm^{-3}), boxplot by depth and by treatment, indicating medians, interquartile ranges and extreme values beyond 95%. The data for bulk density is shown in the boxplots below for 2018, after 4 years of experimentation and at the three sample depths (0-100 mm, 100-300 mm, 300-500 mm).

Bulk density varied between the experimental treatments across the three depths measured (0-100mm depth: p=0.024; 100-300mm depth: p=0.016; 300-500mm depth: p=0.006) (Table 2.7).

Table 2.7 Bulk density (g.cm^{-3}), predicted means and 95% confidence intervals, in 2018 by treatment and by depth

treatment	emmean	lower CI	upper CI
			depth = 0-100mm:
Positive reference	0.86	0.77	0.95
Enhanced	0.83	0.75	0.91
Standard	0.84	0.76	0.92
Negative reference	0.95	0.86	1.04
			depth = 100-300mm:
Positive reference	0.87	0.78	0.96
Enhanced	1.00	0.91	1.08
Standard	0.94	0.86	1.02
Negative reference	1.03	0.94	1.12
			depth = 300-500mm:
Positive reference	0.77	0.67	0.86

treatment	emmean	lower CI	upper CI
Enhanced	0.90	0.82	0.98
Standard	0.90	0.82	0.99
Negative reference	0.93	0.84	1.02

The enhanced was the only treatment with lower bulk density than the negative at the 0-100 mm depth. The enhanced and standard treatments gave greater bulk densities at the 100 to 300 mm compared to 0 to 100 mm depth. At the middle 100-300 mm depth the positive reference was less than the enhanced and the negative reference. The soil had lower bulk density at 300-500 mm depth in the positive reference, than under any other treatments (Table 2.8, Appendix Figure 2.10).

There was no difference between the standard and enhanced treatments, nor was there a correlation between SOM and bulk density (p-value=0.59). The effect of the negative reference on bulk density did not vary with depth.

Table 2.8 Bulk density (g.cm^{-3}), contrasts of treatment pairs at three depths, in 2018 estimate, 95% confidence intervals

contrast	estimate	lower CI	upper CI	p-value
				depth = 0-100mm:
Positive reference - Enhanced	0.034	-0.078	0.146	0.864
Positive reference - Standard	0.022	-0.090	0.134	0.958
Positive reference - Negative r.	-0.086	-0.213	0.041	0.296
Enhanced - Standard	-0.012	-0.107	0.084	0.988
Enhanced - Negative reference	-0.120	-0.232	-0.008	0.031
Standard - Negative reference	-0.108	-0.220	0.004	0.064
				depth = 100-300mm:
Positive reference - Enhanced	-0.124	-0.236	-0.012	0.024
Positive reference - Standard	-0.071	-0.183	0.041	0.362
Positive reference - Negative r.	-0.158	-0.284	-0.031	0.008
Enhanced - Standard	0.054	-0.042	0.149	0.463
Enhanced - Negative reference	-0.034	-0.146	0.079	0.866
Standard - Negative reference	-0.087	-0.199	0.025	0.187
				depth = 300-500mm:
Positive reference - Enhanced	-0.130	-0.252	-0.008	0.032
Positive reference - Standard	-0.137	-0.257	-0.016	0.02
Positive reference - Negative r.	-0.159	-0.294	-0.024	0.013
Enhanced - Standard	-0.007	-0.104	0.090	0.999
Enhanced - Negative reference	-0.029	-0.142	0.084	0.909
Standard - Negative reference	-0.022	-0.134	0.090	0.955

Water Infiltration

Water infiltration readings were taken in three separate years 2015, 2018 and 2019 (Figure 2.6). The model produced non-estimable means for crops which were confounded by years. No difference in effect of overall treatments was found (p-value =0.24).

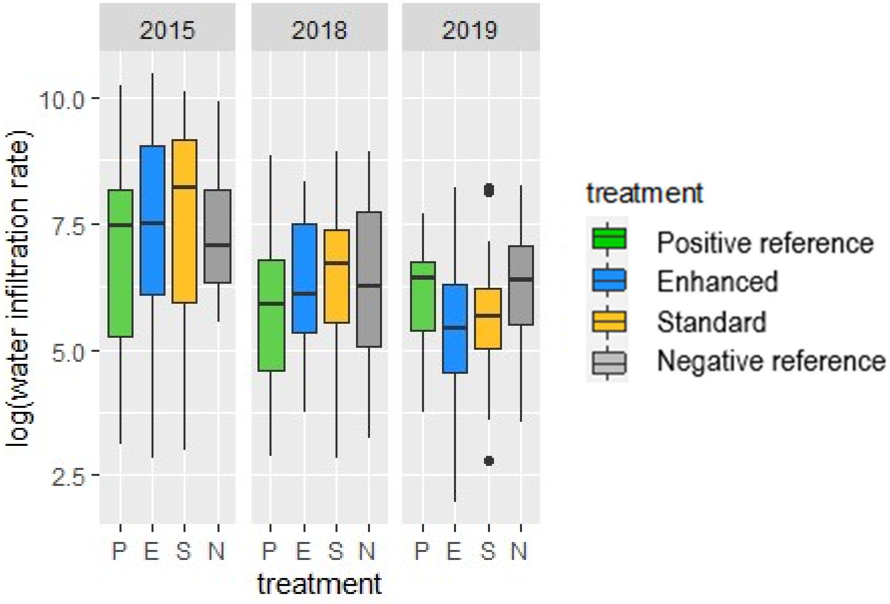

Figure 2.6 Water infiltration log(rate), boxplots, by year and treatment, indicating medians, interquartile ranges and extreme values beyond 95%. P-positive, E-enhanced, S-standard, N-negative

Penetrometer point pressure

The penetrometer point pressure dataset of measurement below 200mm did not allow for a meaningful analysis due to a large proportion of missing values, mostly resulting from high stone content at this depth. At 250mm, 1 in 4 readings and at 325mm, 1 in 3 readings were unobtainable. The observations from 100mm and 200mm soil depths were much more complete and are shown in Figure 2.7.

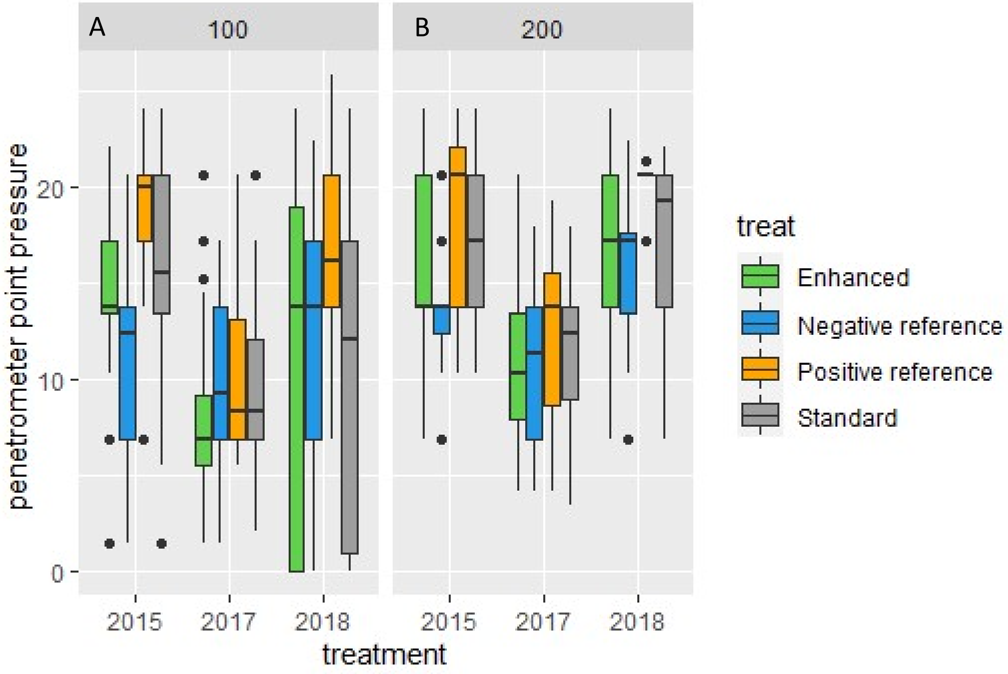

Figure 2.7 Penetrometer point pressure (10^5 Nm^{-2}), boxplot, plot A: depth = 100 mm and plot B: depth = 200 mm, by treatment, indicating medians, interquartile ranges and extreme values beyond 95%

Only data for 2018 was modelled as the most recent and most impacted by the treatments. Comparison between years was not possible due to variations in soil conditions between years. Table 2.9 shows the predicted means by treatment and depth, together with 95% confidence intervals.

Table 2.9 Penetrometer 2018 (10^5N/m^2), predicted means and 95% confidence intervals, by treatment and depth

treatment	emmean	lower CI	upper CI
			depth = 100 mm
Positive reference	16.7	7.79	25.5
Enhanced	11.5	2.35	20.6
Standard	10.7	1.58	19.7
Negative reference	13.4	4.5	22.3
			depth = 200 mm
Positive reference	20.2	17.2	23.2
Enhanced	16.7	14.8	18.6
Standard	17	15.1	19
Negative reference	15.5	13.4	17.7

Soil compaction measured by penetrometer reading was higher in the positive reference treatment at the shallow depth (0-100mm) compared to the enhanced and standard treatments, while positive was higher than negative reference at the 200mm depth, see Table 2.10 and Appendix Figure 2.11. A model of bulk density with penetrometer at the 0-100mm depth failed to converge.

Table 2.10 Penetrometer point pressure 2018 (10^5 N.m^{-2}), contrast of treatment pairs by depth,

contrast	estimate	lower CI	upper CI	p-value
depth = 100 mm				
Positive reference - Enhanced	5.21	0.38	10.03	0.031
Positive reference - Standard	6.00	1.14	10.85	0.010
Positive reference - Negative r.	3.24	-1.98	8.47	0.360
Enhanced - Standard	0.79	-3.49	5.07	0.955
Enhanced - Negative reference	-1.96	-6.65	2.72	0.672
Standard - Negative reference	-2.75	-7.47	1.96	0.403
depth = 200 mm				
Positive reference - Enhanced	3.49	-0.94	7.92	0.168
Positive reference - Standard	3.13	-1.33	7.59	0.256
Positive reference - Negative r.	4.66	0.02	9.29	0.049
Enhanced - Standard	-0.36	-3.62	2.9	0.989
Enhanced - Negative reference	1.17	-2.25	4.58	0.782
Standard - Negative reference	1.53	-1.95	5.01	0.634

Discussion

Five hypotheses relating to soil characteristics were tested in this chapter. 1) Adding biomass increases SOM at 0-100 mm depth, tested by organic matter loss on ignition. 2) Adding biomass increases SOM at depth (100-300 mm), tested by OM loss on ignition. 3) Adding biomass increases labile carbon as an indication of soil health improvement, tested using labile carbon assessment. 4) Adding biomass improves soil water holding capacity, tested by water infiltration rate and bulk density at three depths. 5) Adding biomass lowers soil compaction at various depths, tested by bulk density and penetrometer point pressure. Changes were considered relative to the standard treatment where crop residues are removed, and the two experimental references, a 5-year ley treatment (positive reference) and a routinely tilled fallow treatment (negative reference).

Soil Organic Matter

The diverse ley cropping system in this study, whether shredded crop residues were retained or not, resulted in important increases in soil organic matter. The amount of organic matter in the top 100 mm of soil increased relatively by 1.59% yr^{-1} in the enhanced treatment, by 1.21% yr^{-1} in the standard treatment, and by 3.14% yr^{-1} in the positive reference over the five-year study period. At the 100-300 mm depth SOM did not change in the enhanced and standard treatments but increased by 1.57% yr^{-1} in the positive reference (see below). This easily surpasses the annual 0.4% yr^{-1} COP21 global target of increasing existing SOC stock (4p1000 2015, Minasny et al. 2017). Interestingly, the negative reference showed no change in SOM despite very limited fresh carbon input. Clearly, the introduction of diverse leys into arable rotations could contribute to climate change mitigation in a meaningful way, as also suggested by Paustian et al. (2016). Increased SOM accumulation as a result of ley development fuels improved soil function and the provision of ecosystem services such as drought resistance, flood prevention and nutrient cycling (Acton 1995, Paustian et al. 1997, Dwyer et al. 2015, Minasny et al. 2017). Farmland biodiversity stands to benefit from increases in SOM due to above- and below-ground biota impacts (Mader et al. 2002, Gilroy et al. 2008, Sylvain and Wall 2011, Thiele-Bruhn et al. 2012).

These soils are resilient, no decline in SOM was observed in the negative reference treatment after 5 years of fallow treatment. The negative reference was routinely tilled to 75mm to achieve minimal plant growth. The continued activity of heterotrophic organisms in the soil was expected to slowly degrade existing SOM (Loveland and Webb 2003, Bellamy et al. 2005, Smith 2008, Gougoulias 2014), but this was not seen. Illustrating the resilience of the soil system and the length of time needed to observe any changes in soil carbon content (Hendrix et al. 1998), particularly with the lack of topographical gradient at the study site which minimised erosion of the bare soil (Montgomery 2007).

Lengthening the ley phase duration increased carbon sequestration in soil organic matter and increased its carbon sequestration potential. Carbon sequestration rate increased in these longer-term leys, there was a clear indication of greater carbon sequestration potential of this longer-ley management option. Further, no upper limits were established in this experiment within the 5-year ley. This positive reference treatment added 1.6 $g.kg^{-1}.yr^{-1}$ SOM, irrespective of the initial level of SOM content. This differs from the enhanced and standard treatments, where the SOM increase was smaller in plots that had more SOM at the start of the experiment. The varying ability of arable soils to increase the absolute level demonstrated here has important consequences for soil carbon sequestration potentials (Powlson et al. 2011, Amundson and Biardeau 2018). Soil carbon concentration is a function of soil texture, climate, and management (Hendrix et al. 1998, Chung et al. 2010, Beare et al. 2014) and is driven by the soil microbial communities and enhanced by plant diversity (Lange et al. 2015), with a peak reached when the system is in equilibrium. Two long-term experiments in the UK in mixed farming systems, firstly at Woburn showed that a rotation of 2-years conventional arable-with a grass/clover 3-year ley, on sandy loam soil, increased C by 0.28% C (~4.83 $g.kg^{-1}$ SOM) after 33 years, secondly at Rothamsted a 3 year arable with 3-year grass/clover ley, on silty clay loam soil, increased C by 0.23% C (~3.97 $g.kg^{-1}$ SOM) over 36 years (Johnston et al. 2009). In a US study converting row cropping to pasture with intensive grazing, Machmuller, Kramer et al. (2015) demonstrate a carbon sequestration curve reaching equilibrium after 6 years, accumulating SOM at 8.0 Mg C ha^{-1} yr^{-1}. The study in this chapter demonstrates the possibility of increasing SOM content well above global targets. In addition, this shows that the carbon saturation point of an agricultural soil can be increased using realistic changes to the cropping and land management systems.

Soil Organic Matter at depth

The diverse ley maintained throughout the duration of the experiment with no mechanical tillage (positive reference), was the only treatment that resulted in a change in SOM at the 100-300 mm depth. There was a 3.0 $g.kg^{-1}$ SOM increase at this depth after five years, together with a reduction of bulk density at this depth. These effects may accrue from what is termed here - bio-cultivation of soil - a combination of mechanisms driven by the interactions of diverse plant and soil biota communities (Mueller et al. 2013). The activity of roots at depth increases movement of air, water and biota through the soil and drives improvements in the aggregation of soil particles (Lavelle et al. 2006, Bardgett and van der Putten 2014, Wagg et al. 2014). The diverse ley in the positive reference included several deep rooting species such as *Cichorium intybus* (common chicory), *Onobrychis vicifolia* (common sainfoin) and *Medicago sativa* (alfalfa also called lucerne) (Wilkinson 2020). In addition, the diversity of plant communities may be more important for deep rooting than the presence of plants with deep rooting traits (Mueller et al. 2013). The observed difference at 100-300 mm depth between the positive reference and the two biomass treatments suggests that the length of the ley phase (5 vs 2 years) appears to have more impact than returning crop residues to the soil (enhanced vs standard). Building up SOM, particularly at depth, may thus be more effectively achieved by growing diverse root communities over time, rather than returning above-ground biomass to the soil.

At 300-500 mm soil depth the positive refence bulk density was lower than the other treatments, perhaps indicating greater root penetration due to diverse root activity over 4 years (Goss and

Watson 2003, Mueller et al. 2013). SOM was not measured at this depth, however given the increase in SOM at 100-300 mm noted above this bulk density result might suggest an increase in SOM (Abdollahi et al. 2014, Belmonte et al. 2018) at 300-500mm as well?

Labile Carbon

More labile carbon was seen across all biomass addition treatments than in the negative reference. Increased labile carbon in the soil provides energy and nutrients that drive the physiology of soil microorganisms (Malik et al. 2018). The activity of these organisms then contributes to the process of soil aggregation, stabilising soil organic matter and improving soil function (Tisdall and Oades 1982, Chantigny et al. 1997). Contrary to the work of Xu et al. (2011) there was no correlation between labile carbon content in 2019 and (the rate of) change in SOM in this experiment. This experiment suggests an alteration of the SOM transformation process (Liu et al. 2006) , possibly as a result of crop residue quality or indeed a shift in the composition of soil biota (Dignam et al. 2019). The growth of diverse ley mixture of grasses, herbs, and legumes in this study resulted in similar amounts of labile carbon to the annual cereal crops. Several mechanisms may explain this, including an interaction between legumes and herbs driven by N availability (Carlsson and Huss-Danell 2003), although there was not sufficient data to explain this process fully.

Soil compaction and water holding capacity

Bulk density was lower at the 0-100 mm depth in the enhanced treatment compared to the negative reference, perhaps explained by tillage together with biomass retention. Bulk density worsened below tillage depth (100-300 mm) in the enhanced and standard treatments (the negative treatment was already high at the surface, see Appendix Figure 2.10). At 300-500 mm soil depth the positive refence bulk density was lower than the other treatments (as already noted in SOM at depth section above) implying positive impact from the diverse species mixture’s long-term rooting traits (Goss and Watson 2003, Mueller et al. 2013).

At the shallow depth (100 mm) penetrometer readings were higher in the positive reference treatment compared to all other treatments, positive was still higher than the enhanced treatment at the 200mm depth. The higher readings in the positive reference could be explained due to lack of tillage compared to all the other treatments, also because of the generally high clay content leading to strong particle bonding without water (Hadas and Wolf 1983, Hu et al. 2015).

This experiment was not able to demonstrate any changes to water infiltration rate. Water infiltration and its subsequent retention in the soil is important in buffering high rainfall events and in mitigating drought and flood events. Soil compaction impacts water and air infiltration. The improvements in bulk density are linked to likely positive impacts on water and air ingress which would typically improve plant growth and soil organism activity and ease tillage (Obour et al. 2018).

Changes in organic matter content are associated with soil physical attributes (Abdollahi et al. 2014, Belmonte et al. 2018), but in this experiment changes in bulk density were not associated with a measurable change in SOM. Bhogal et al. (2009) found that relatively large amounts of organic carbon inputs are required to change soil physical properties. A future improvement of water infiltration may result from observed SOM accumulation, however no evidence of these improvements was seen within the 5 years of the experiment. This could be accounted for by the soil improvements to the experimental site prior to the study from over ten years of reduced tillage and diverse leys with animal grazing (Reeder and Schuman 2002).

Retention of crop residues

Retention of crop residues did not affect any of the response variables explored in this Chapter. Fertility-building diverse leys were integrated into all rotations observed in this experiment (except the negative reference). At least 2 years of diverse ley were used as a fertility building phase during the five years of the study in each biomass addition treatment. As the standard treatment did not retain any above ground plant biomass, the diverse root systems of the 2-year diverse ley are likely to have provided sufficient biomass input and root exudates (Mueller et al. 2013, Yang et al. 2019) to support the cash crops proceeding in the rotation. There was no change in SOM, between the enhanced treatment which retained aboveground biomass, implying the gains achieved in SOM above the negative reference were due to below-ground activity. In a review of different cropping studies, root inputs were on average 8.1 times more effective at stabilising SOM than the same mass of above ground litter (Jackson et al. 2017). From this experiment, it can be inferred that carbon sequestration begins with just 2 years of diverse ley pasture. Machmuller et al. (2015) found that after a conversion from crop to pasture, SOM accumulation did not start until after year two.

Carbon Capture

Mixed diverse ley farming systems can sequester amounts of carbon well beyond global targets. This study shows that in addition to the introduction of leys into arable rotations, increased amounts of carbon can be sequestered by increasing the length of the ley phase. This may have economic consequences for the farming system by reducing annual cropping and increasing animal utilisation of the diverse ley. At a time when there is increased attention to the climate impact of animal production/husbandry, the use of diverse leys to support both ruminant and monogastric animal production (Fog et al. 2017, Santamaria-Fernandez et al. 2017) could make an important and valuable contribution to off-setting their emissions (Dumont et al. 2020). This experiment confirms the carbon capture potential of diverse leys over a 5-year period. In a key finding, the global impact of introduction of the diverse ley over a much shorter 2-year period could be far more important. This intervention can be widely adopted in crop rotation systems to mitigate climate change. SOM accumulation in arable cropping systems can be achievable to a depth of 100mm and below at rates more than 3 times greater than the COP 21 global target of increasing carbon stocks by 0.4% annually.

Conclusion

The diverse ley cropping system in this study, whether shredded crop residues were retained or not, resulted in globally important increases in soil organic matter. In addition, this study shows that the carbon saturation point of an agricultural soil can be increased using realistic changes to the cropping and land management systems. Building up SOM, particularly at depth, may thus be more effectively achieved by growing diverse root communities over time, rather than returning above-ground biomass to the soil.

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Appendix of supplementary information

Soil Organic Matter

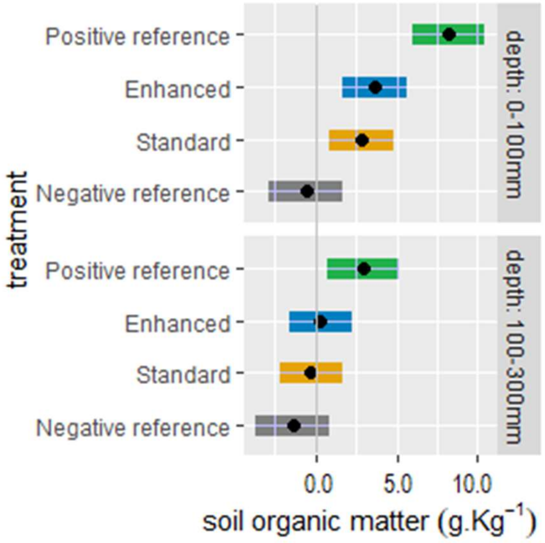

Figure 2.8 Change in SOM between 2014 to 2019 (g.kg^{-1}) in four plant biomass treatments: enhanced (retention of all crop residue in situ), standard (removal of residues, business as usual), positive reference (5 year ley), and negative reference (no plants). Dots show predicted means by treatments and depth, bars represent 95% confidence intervals.

Table 2.11 Relative change (%) in SOM between 2014 to 2019 with 95% confidence intervals. Calculated as % annual relative change in SOM = (((((SOM2019 - SOM2014) / SOM2014) + 1) ^(1/5)) - 1) * 100

treatment	emmean	lower CI	upper CI	p-value
				depth = 0-100mm:
Positive reference	3.15	2.12	4.18	<0.001
Enhanced	1.59	0.69	2.51	0.003
Standard	1.21	0.30	2.12	0.014
Negative reference	-0.30	-1.33	0.73	0.549
				depth = 100-300mm:
Positive reference	1.57	0.06	3.09	0.044
Enhanced	0.22	-1.28	1.72	0.723
Standard	0.00	-1.50	1.50	0.995
Negative reference	-0.67	-2.18	0.85	0.337

Labile Carbon

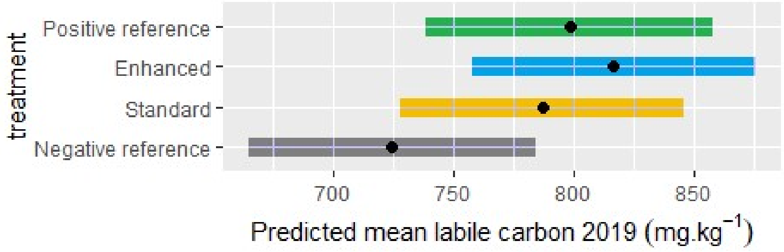

Figure 2.9 Labile carbon at 0-100 mm depth, plot of predicted means and 95% confidence intervals by treatment mg.kg^{-1}

Bulk Density

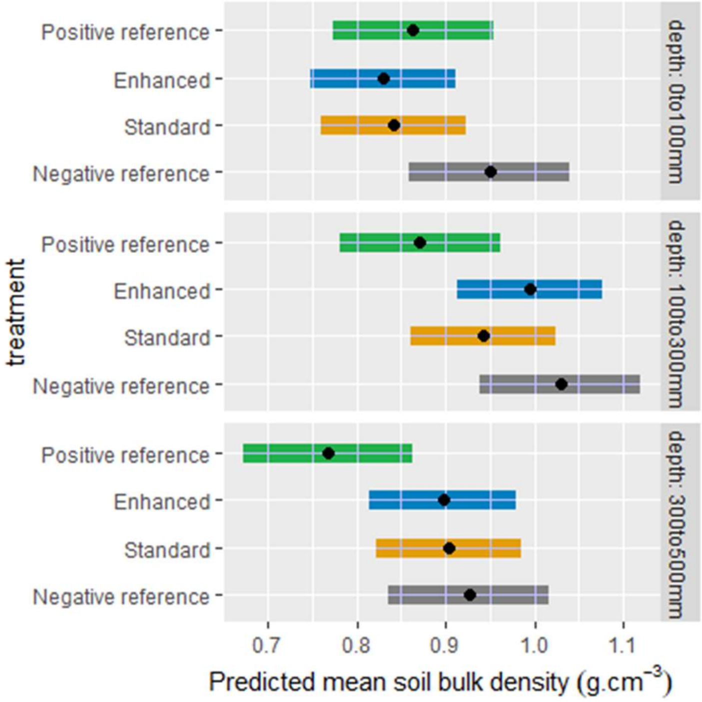

Figure 2.10 Bulk density, plot of predicted means 2018, at 0-100 m, 100-300 mm and 300-500 mm depths, with 95% confidence intervals

Penetrometer point pressure

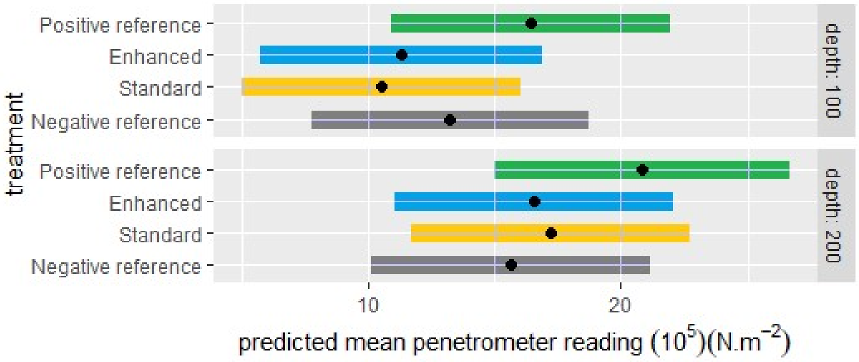

Figure 2.11 Penetrometer point pressure 2018 (10^5 N/m^2), plot of predicted means and 95% confidence intervals at 100 mm and 200 mm depth,

Chapter 3. Soil Biota Characteristics (Second order effects)

Introduction

The decline in biodiversity and the degradation of soils are interconnected, human induced, global threats to the Anthropocene (Gilroy et al. 2008, Bindraban et al. 2012, Newbold et al. 2015, Borrelli et al. 2017). These threats must be addressed across all working landscapes (forest, range- and farmland), it is not sufficient to rely upon increasingly vulnerable and fragmented protected-areas to preserve biodiversity (Kremen and Merenlender 2018).

Organic farming is an alternative farming method that uses the ecological intensification approach (Tittonell 2014) to address current agricultural challenges, resulting in improved biodiversity and increased soil organic matter (Mader et al. 2002, Birkhofer et al. 2008, Gattinger et al. 2012). Organic systems restrict the use of artificial fertilisers and agrochemical pesticides and therefore come with challenges such as weed control and potential yield penalties (de Ponti et al. 2012, Seufert et al. 2012, Tittonell 2014, Röös et al. 2018).

Soil is the focus in healthy organic farming systems (Acton 1995, Stockdale and Watson 2009), with its fertility being improved by the use of short term leys, green manures and livestock (Watson et al. 2002). Leys and green manures increase fertility through nitrogen-fixing legumes and SOM accumulation (Poeplau and Don 2015). This fertility together with crop rotation, crop species and crop variety selection can improve yields through weed and pest suppression, improved water holding capacity, nutrient cycling and disease reduction (Schipanski et al. 2014).

An active soil community, comprising macrofauna, mesofauna and micro-organisms including fungal networks, facilitates the positive effect of leys and green manures on soil fertility. This soil community processes plant material deposited by the plants. They also make nutrients accessible by mineralizing organic matter (Hodge et al. 2000, Zagatto et al. 2019), control soil organic carbon storage (Moorhead and Sinsabaugh 2006), contribute to the structural stability of soil aggregates (Abiven et al. 2009, Six and Paustian 2014), suppress soil-borne plant pathogens (Janvier et al. 2007, Senechkin et al. 2014, van Bruggen 2015) and, as a consequence, affect plant health and crop yield (Bonanomi et al. 2016). Below ground biodiversity is therefore a key resource for maintaining ecosystem functionality (Wagg et al. 2014), the belowground decomposer system provides the basis for soil fertility and plant life (Scheu et al. 2005). The “value of these ecosystem services to agriculture is enormous and often underappreciated” (Power 2010), with organic agricultural systems fostering microbial and faunal decomposers (Birkhofer et al. 2008) making a virtuous circle.

Soil fauna, a part of the soil community, contribute an important connection between plants and soil especially through the cycling of leaf litter (Birkhofer et al. 2011, Frouz 2018). However, there are many factors affecting soil fauna that remain unexplored, particularly at large spatial and temporal scales (Birkhofer et al. 2011). Soil macrofauna, such as earthworms, is widely credited with its soil improvement skills (Jouquet et al. 2006), whilst the soil mesofauna is a lesser known group of soil fauna (Wagg et al. 2014) categorised by their body width (100µm-2mm).

Mesofauna

The soil mesofauna comprises microarthropods, the mites (Acari) and springtails (Collembola), and white worms (Enchytraeidae).

King and Hutchinson (1976) have shown seasonal fluctuations in the abundance of mesofauna in grasslands for Collembola, Acari, Enchytraeidae and Nematoda. Consistent seasonal rhythms in numbers were observed for Collembola and Acari, peak numbers occurred in late Summer for Collembola and in Winter for Acari (King and Hutchinson 1976). Changes in mesofauna abundance were related to changes in herbage, litter, roots, soil pore space, and soil temperature. For example, increased sheep numbers severely reduced the numbers of Collembola, particularly the surface dwellers (0-5 cm) (King and Hutchinson 1976). Use of anthelmintic, pyrethroid and organophosphate animal pesticides can also affect soil microbial activity, soil invertebrate mortality and reproduction (Boucard et al. 2008, Jensen et al. 2009). A recent review by Gunstone et al. (2021) shows that pesticides of all types pose a clear hazard to soil invertebrates.

Collembola and Acari populations are greater in soils under annual crops and in soils with crop rotation (Neher and Barbercheck 1998), which may be due to reduced soil surface compaction without animal grazing and reduced competition from larger macrofauna which may be more vulnerable to tillage.

Enchytraeids and Collembola are ecosystem engineers, alongside earthworms (Davidson et al. 2002, Stockdale 2006, Briones 2014, Frouz 2018), particularly in more acidic soils (Scheu et al. 2005).

Mesofauna consume three quite different energy sources supplied by plants to the soil community (Moore et al. 1988; de Ruiter et al. 2002) as cited in (Scheu et al. 2005): root exudates; living plant roots; and plant debris (Scheu et al. 2005). Acari feed either on soil microflora or on dead plant material and are generally detritivorous. Collembola feed mostly on fungi but also on bacteria or algae (Scheu et al. 2005). Enchytaeidae are assumed to be 80% microbivorous (bacteria and fungi) and 20% saprophagous (Didden et al. 1997) in (Scheu et al. 2005).

Mesofauna activity releases high nitrogen (N) faecal pellets available to plants as part of the soil N cycle (Frouz 2018). They consume carbon and temporarily immobilise nutrients in their bodies, reducing the leaching of nutrients. In general, grazing by mesofauna on microorganisms stimulates decomposition processes and results in increased mineralization of nutrients with important feedbacks to plant growth (Scheu et al. 2005). Soil fauna is an important part of the feedback loop between plant and soil properties (Frouz 2018).

Given the broad range of functions described above, mesofauna are a key group of soil biota (Birkhofer et al. 2011, Grandy et al. 2016, Frouz 2018). Mesofauna are a lesser explored group of soil organisms which can contribute to a healthy soil and plant ecosystem, but little is known about their responses to plant biomass addition to the soil via leys and green manures. This research aims to address a gap in understanding of this process by assessing how soil mesofauna numbers react to additions of plant biomass and retention of crops residues in an agroecological system.

Disease reduction

Alongside their role in nutrient cycling, mesofauna, specifically Collembola have a role in disease suppression. As fungal feeders they perform a functional service in consuming soil-borne plant pathogens (Neher and Barbercheck 1998), which include diseases such as take-all and brown foot rot, which are important fungal diseases in wheat (Sabatini and Innocenti 2001).

A review of evidence indicates that increasing amounts of crop residues, particularly in humid temperate climates under reduced tillage systems, might encourage pathogen survival (Bockus and Shroyer 1998); but diverse microbial populations (Kerdraon et al. 2019) and activity in the root zone of a healthy soil can prevent root diseases from developing (Sturz et al. 1997).

This study looks at the gap in knowledge where crop residues are retained in agroecological systems to explore their impact on plant disease levels. The mesofauna contribution to soil function is indirectly assessed here by looking at crop leaf senescence, used in this experiment as a measure of assessing plant fungal resistance.

Soil Aggregate Stability

Soil biota provide many different soil functions, for example leaf litter decomposition and SOM protection, which are critical processes in carbon sequestration (discussed in Chapter 2). Soil structure is provided by the action of many different soil organisms in gluing soil particles together using glycoproteins and polysaccharides (Edwards and Bremner 1967, Tisdall and Oades 1982). Although arbuscular mycorrhizal fungi are well-known for their impact on aggregating soil particles they are not the only biota involved (Morris et al. 2019). Mesofauna are instrumental in leaf litter decomposition, which can result in the priming of SOM degradation and carbon cycling, by contributing to particulate organic matter (POM) and light fraction organic matter (LFOM); also known as labile carbon (Frouz 2018). Labile carbon was shown to be higher in all the biomass addition treatments in Chapter 2 and is an indicator of the available thermodynamic energy needed for SOM degradation (Bosatta and Ågren 1999, Lehmann and Kleber 2015). The effects of fauna on SOM dynamics may be more important in dynamic than in stable ecosystems (Frouz 2018). A stable ecosystem will be in near balance, with an established community of soil fauna adapted to existing organic matter inputs. In a system in transition, on the other hand, soil fauna has to adapt to changes in resource availability and is likely to have a stronger effect on SOM. Research in India has shown that retention of crop residues in no-till conventional cropping can increase soil aggregation (Singh et al. 2018). Whereas tillage provides an opportunity for dynamic change, which is rapidly exploited by opportunistic predators such as Collembola followed by Acari (Neher and Barbercheck 1998).

Mesofauna are consumers of easily decomposed polysaccharides and soluble polyphenols, both of which act as soil glue, whether this has a positive or negative effect on SOM dynamics is unknown. It is unclear from the literature whether retaining crop residues increases aggregate stability in tilled agroecological systems using diverse leys and green manures; and whether increased labile carbon could have a negative impact upon soil aggregation. This study aims to address this knowledge gap.

Weed burden

Leys and green manures are frequently used in organic farming systems to provide a break in the weed life cycle, by reducing the viability of weed seeds stored in the soil seedbank (Gómez et al. 2014) and by allelopathy (Putnam and Duke 1978). Liebman and Davis (2000) found in their study the additions of organic matter can reduce weed density and growth while maintaining crop yields. Weed seed survival is also thought to be affected by soil organism community (Chee-Sanford et al. 2006, Mitschunas et al. 2008, Ullrich et al. 2011, Gómez et al. 2014) including predation by soil fauna, small mammals and birds (De Cauwer et al. 2011). However weed seedling emergence can also increase with soil organism activity, for example, collembola can reduce fungi-induced seed mortality (Mitschunas et al. 2008).

Weeds can also be virtuous and supply important provision of many ecosystem services (Hill and Ramsay 1977), including flowers for pollinator services, roots for enhanced soil biota dynamics (Mueller et al. 2013), and seeds and biomass to feed above and below ground biodiversity (Leake et al. 2004, Frouz 2018). Indeed reduction of weeds and soil degradation is implicated in farmland bird decline (Storkey and Westbury 2007, Gilroy et al. 2008).

Weed burden gains much attention in the agroecological context where the impact of weeds upon yield is feared, weeds being the single most important issue facing farmers (Wortman et al. 2010, OKNetArable 2017). This implies a gap in weed knowledge. Increased understanding of weed outcomes in agroecological systems could encourage cropping systems that do not rely upon agrochemicals. Identifying weed outcomes, such as change in weed numbers and weed biomass in varying biomass input systems, could help address this farmer fear of weeds by contributing to this gap in weed knowledge. There are also a few papers that have studied whether retaining crop residues impact weed burden.

This study aims to address the knowledge gaps described above by using a replicated experiment on a commercial organic mixed farm over five years (2014-2019) to investigate the impacts of high biomass rotation including the retention of crop residues in an ecologically intense annual cropping system. One of the goals of this research was to make its findings directly relevant to current agricultural practice, to that end all treatment-plot work was carried out by existing farm equipment. This includes interventions such as combine harvesting, tillage and sowing. The objective of this chapter is to assess whether feeding the soil, through the four experimental treatments, affects the quantity and diversity of soil mesofauna, affects plant senescence rate (which is an indicator of disease pressure), affects soil aggregate stability and to assess the effect of experimental treatments on weed burden.

This chapter tests the following four hypotheses:

1. Adding biomass increases soil mesofauna numbers; tested by trapping and counting mesofauna.
2. Adding biomass reduces plant-fungal load; tested by measuring leaf senescence in crop flag leaves.
3. Adding biomass increases soil aggregate stability; tested by measuring soil particle stability under rapid wetting (slake test, which measures the ability of soil aggregates to withstand hydraulic and physical perturbations).
4. Adding biomass reduces weed burden, tested by measuring weed biomass and counting weed numbers (Chapter 4 looks at crop yield and quality outcomes from the treatments).

Changes will be considered in an enhanced treatment where crop residues are retained, relative to a) the standard treatment where crop residues are removed, and b) the two experimental references: a 5-year ley treatment (positive reference) and a routinely tilled fallow treatment (negative reference).

Methodology

Site description and Experimental Design

These are detailed in Chapter 2.

Measurement and sampling protocols

Soil samples from each treatment-plot were collected and labelled in November 2018 for the mesofauna study. One sample site per each treatment replicate was randomly chosen within the treatment-plot using the resting position of a thrown ball. A soil corer was then used to collect a soil core 80 mm diameter x 150 mm depth. Bagged soil samples were stored at 4^oC for one month until heat treated. The samples were individually placed within Tullgren funnels. A wire mesh at the bottom prevented the soil from passing through whilst allowing gaps for soil fauna to pass. Individual bulbs sited directly over each funnel acted as a heat source to stimulate the soil fauna migration downwards, away from the heat and light, through the soil profile, mimicking natural conditions. Pots containing 100 ml of 70% ethanol were placed below each funnel to catch and preserve the extracted fauna (Marks 2019). The mesofauna were separated, identified (Tilling 1987) and counted.

Leaf senescence was measured by randomly collecting 20 crop flag leaves of oats, within a one metre quadrat chosen randomly in Excel using coordinates within each full-size-plot quarter. These were then assessed for senescence as a percentage yellow leaf area (Bresson et al. 2018).

Soil aggregate stability following rapid wetting was assessed in September 2018 using the Slake test (Arshad et al. 1997, USDA 2020). A soil pit was dug first to 100 mm and then to 300 mm; about 200 g of soil was taken and placed in a labelled sample bag at each depth and stored in a cool area. Four mid-sized aggregates were selected from each sample and laid out on a labelled tray to dry for 5 days at room temperature. Afterwards, the aggregates were submerged completely into 500 ml of rainwater and scored using the soil stability scoring system, firstly after five minutes and secondly after two hours. The best scores were 0 where the aggregates remained intact, 1 if the lump collapses around the edges but remains intact, 2 if the lump collapses into angular pieces, 3 if the lump collapses into less than 2 mm pieces and the worst scores were 4 where the soil completely collapsed when wet. Assessments were carried out at Plymouth University. Soil Organic Matter (SOM) analysis was carried out in 2018. Soil samples were taken in September by first splitting each full-size-plot into quarters, then using the centre line of each plot a soil core sample was taken 10 m from the start line of each full-size-plot quarter. The auger was inserted by twisting 500 mm into the ground and removed carefully so as not to disturb the core. The core was then separated into buckets in two depths: 0-100 mm and 100-300 mm. This resulted in 2 samples per sampling site, 4 sampling sites per full-size-plot (2 sampling sites per reference-plot), 36 sites per field, 144 sites, and 288 samples across the whole farm. The soil samples were then analysed at Plymouth University for SOM using a furnace temperature of 550 ^{O}C (Hoogsteen et al. 2015). This contrasts with 430 ^{O}C furnace temperature used at NRM laboratories in the SOM analyses of Chapter 2.

Weed Burden: weed species individuals (*Rumex* (docks), *Avena* (wild oats), *Sinapis arvensis* (charlock), *Cichorium intybus* (chicory), *Taraxacum officinale* (dandelion), Poaceae (grasses) were counted within one square metre quadrats at the sample sites (see Chapter 2 Experimental Design), which were chosen randomly in Excel using coordinates within the full-size-plot quarters (4 samples per full-size-plot, 2 samples per reference-plot), in late June or early July 2015, 2017, 2018 and 2019. An assessment in percentage ground cover was made for grasses and for total weeds. Total weeds were collected and weighed for biomass, stored and air-dried in a grain store to reach constant moisture content for one month and reweighed for biomass (a practical on-farm solution to achieve homogenous moisture content samples).

Statistical analysis

Data was stored and validated for completeness and boxplots were made of all the assessments to identify any extreme values and explore the distribution of the data. All treatment assessments (except soil sample for mesofauna counts) were conducted at four sampling sites within each full-size-plot (two sampling sites in each reference-plot). To account for the pseudo replication, the results are analysed using a nested mixed model with treatment-plot (see chapter 2 experimental design) nested in replicate and replicate nested in field (1|field/replicate/treatment-plot). Field, replicate, and treatment terms were treated as random effects to improve applicability of the results to other farms or fields. Mixed models were used to analyse all the responses, with a support distribution as required by each outcome, namely: Normal; Lognormal; Poisson; Beta (Brown 2015). Soil samples, to conduct mesofauna counts, were taken at one per treatment-plot. Poisson distributions were used to model the total mesofauna, Acari and Collembola counts, separately. These models used SOM 0-100 mm in 2014 (see Chapter 2), SOM 0-100 mm in 2018 (adjusted, see below), bulk density 0-100 mm in 2018 (see Chapter 2) as covariates and treatments as factor. However, adding the covariates did not improve the model performance so they were dropped. The models for *Sminthuridae,* Coleoptera and Hemiptera had singular fits deemed to be too close to zero and were excluded. The SOM 2018 data was analysed using a furnace temperature of 550 ^{O}C (Hoogsteen et al. 2015), 430 ^{O}C is the common agricultural practice (NRM 2019), avoiding oxidation of the calcium carbonate from the parent material that may be present in a soil sample, this also avoids removal of water bound tightly in clay particles (Howard and Howard 1990). At depth (100-300 mm), there was no correlation between the 2018 data and the 2019 data (tested with different furnace temperatures). SOM 2018 data at 0-100 mm was explored, two outliers were removed as they made no scientific sense and were likely to be mistakes or extreme reactions to the method due to high $CaCO_3$ in the samples. SOM level in 2018 was plotted against SOM level measured in 2019 to determine the strength of the bias due to the higher furnace temperature. The linear regression model was highly statistically significant (p-value <0.001) and a correction factor of 0.85 was calculated for SOM2018 (Figure 3.1).

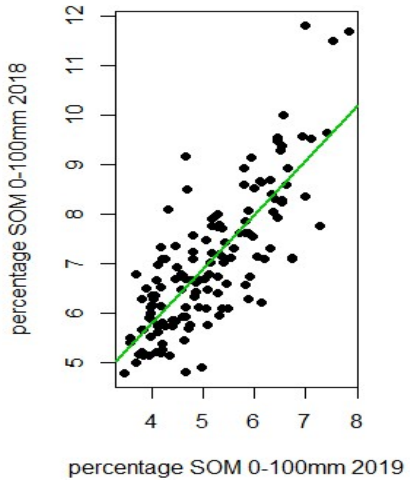

Figure 3.1 Two Plots showing comparisons of 2018 and 2019 SOM plot with 2 outliers removed, green regression line with outliers removed.

This allowed for adding SOM 2018 0-100 mm data to the Mesofauna model with a reduction factor of 0.85 (hence SOM 2018(adjusted).

A Normal distribution was used to model leaf senescence and aggregate distribution scores. A Lognormal distribution was used to model both fresh and dry weed biomass. A Beta distribution was used to model visual percentage assessment records. Poisson distributions were used to model weed counts. In interpreting the results some statistically significant results are shown to be of such small effect to be of no practical importance, these are noted. P-values of less than 0.05 were deemed indicative of statistically significant effects. The data was analysed and modelled in R, version 4.1.0. The denominator degrees of freedom were computed by the Kenward-Roger method.

Results

Soil Mesofauna

The following mesofauna were identified in soil samples taken from experimental plots: Collembola (some of which *Sminthuridae*, counted separately as easily identified and checked for significance), Acari (some of which Oribatida and some *Astigmatina*, both counted separately as easily identified and checked for significance), also 3 small invertebrates Coleoptera, Diptera and Hemiptera, were observed, recorded and checked for significance. Figure 3.2 illustrates the mesofauna and total mesofauna (Collembola+Acari) identified and counted in each treatment.

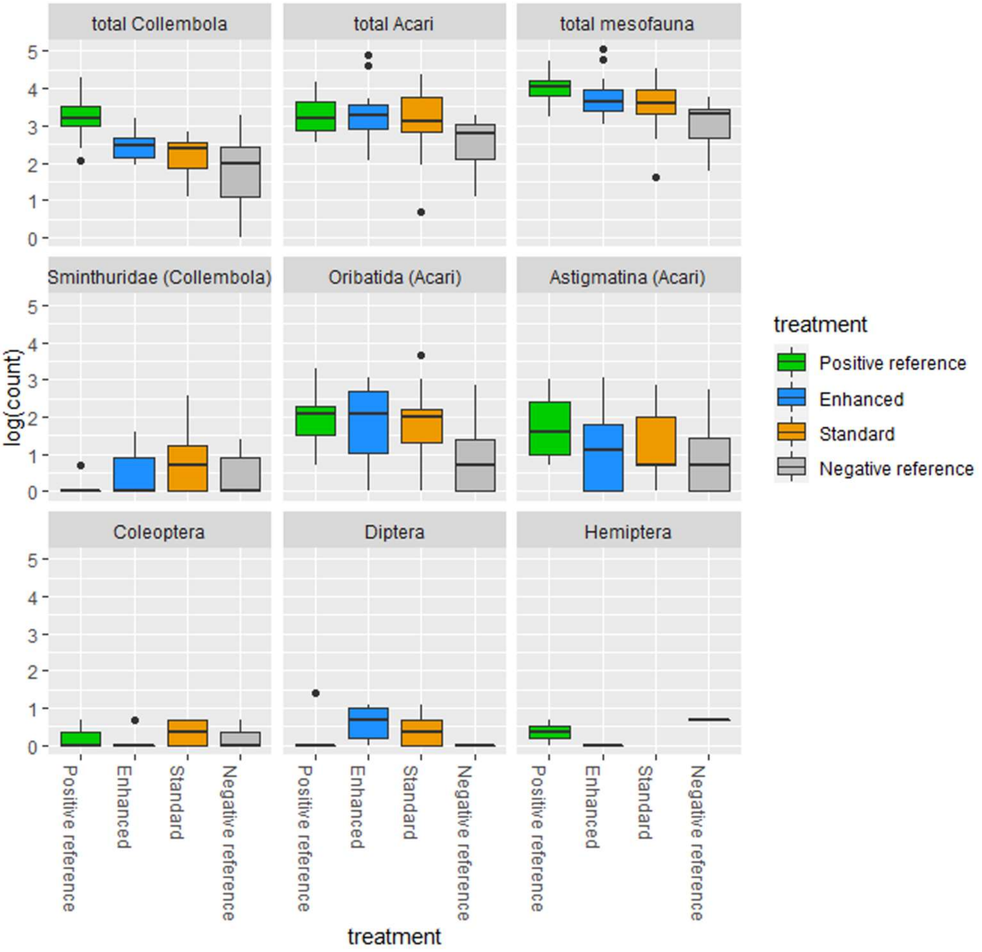

Figure 3.2 Mesofauna log(counts), boxplot, families and mesofauna total (showing medians, interquartile ranges and limits of data) by treatment

Most mesofauna counts were different as a result of the treatments (total mesofauna p<0.001; Collembola p<0.001; Acari p<0.001; Oribatida p<0.001; *Astigmatina* p<0.001, this tests H_o -the true means of all 4 treatments are identical), excepting Diptera (p=0.18). *Sminthuridae,* Coleoptera and Hemiptera were deemed too close to zero and excluded. Outcomes of the models are shown in Table 3.1 (and Appendix Figure 3.5).

Table 3.1 Mesofauna counts predicted means with 95% confidence intervals.

treatment	rate	asymp.LCI	asymp.UCI
Mesofauna total			
Positive reference	55.1	39.9	76.2
Enhanced	51.4	37.2	71.2
Standard	38.6	27.9	53.6
Negative reference	22.8	16.3	31.8
Collembola			
Positive reference	27.75	21.97	35.0
Enhanced	12.14	9.29	15.9
Standard	9.46	7.19	12.5
Negative reference	8.35	6.29	11.1
Acari			
Positive reference	25.8	16.61	40.0
Enhanced	36.2	23.37	56.0
Standard	27.0	17.38	41.8
Negative reference	13.3	8.44	20.8
Oribatida (Acari)			
Positive reference	6.78	3.83	11.98
Enhanced	6.93	3.91	12.29
Standard	7.41	4.2	13.06
Negative reference	2.79	1.51	5.18
Astigmatina(Acari)			
Positive reference	5.84	2.83	12.04
Enhanced	3.64	1.72	7.70
Standard	3.35	1.59	7.06
Negative reference	1.92	0.88	4.19
Intervals are back transformed from the log scale			

The contrasts of treatment pairs are shown in Table 3.2. The enhanced treatment gave more total mesofauna and Acari than the standard treatment. The positive reference and enhanced treatments were not different in total mesofauna counts. Total Acari were particularly responsive to the enhanced treatment but also responsive to standard and positive reference above the negative. Oribatida responded to all treatments with more biomass input compared to the negative reference. Collembola were very responsive to the positive reference and they were more responsive to the enhanced than the negative reference whereas the standard was not different to the negative. The enhanced treatment and positive reference gave higher counts than the negative reference in all cases.

Table 3.2 Mesofauna counts, predicted contrasts of treatment pairs, lower and upper confidence intervals, and p-values

Contrast of treatment pairs	ratio	Lower CI	Upper CI	p-value
Mesofauna total				
Positive reference / Enhanced	1.07	0.93	1.24	0.605
Positive reference / Standard	1.43	1.23	1.66	<0.001
Positive reference / Negative c.	2.42	2.03	2.89	<0.001
Enhanced / Standard	1.33	1.14	1.56	<0.001
Enhanced / Negative reference	2.26	1.88	2.72	<0.001
Standard / Negative reference	1.70	1.41	2.05	<0.001
total Collembola				
Positive reference / Enhanced	2.29	1.77	2.96	<0.001
Positive reference / Standard	2.93	2.24	3.85	<0.001
Positive reference / Negative c.	3.32	2.50	4.42	<0.001
Enhanced / Standard	1.28	0.93	1.77	0.190
Enhanced / Negative reference	1.45	1.04	2.03	0.020
Standard / Negative reference	1.13	0.80	1.60	0.785
total Acari				
Positive reference / Enhanced	0.71	0.59	0.86	<0.001
Positive reference / Standard	0.96	0.79	1.16	0.932
Positive reference / Negative c.	1.94	1.54	2.46	<0.001
Enhanced / Standard	1.34	1.12	1.61	<0.001
Enhanced / Negative reference	2.73	2.17	3.43	<0.001
Standard / Negative reference	2.03	1.61	2.57	<0.001
Oribatida (Acari)				
Positive reference / Enhanced	0.98	0.68	1.42	0.99
Positive reference / Standard	0.92	0.64	1.31	092
Positive reference / Negative c.	2.43	1.50	3.92	<0.001
Enhanced / Standard	0.94	0.65	1.34	0.97
Enhanced / Negative reference	2.48	1.53	4.02	<0.001
Standard / Negative reference	2.65	1.65	4.26	<0.001

Contrast of treatment pairs	ratio	Lower CI	Upper CI	p-value
				Astigmatina (Acari)
Positive reference / Enhanced	1.60	1.01	2.54	0.04
Positive reference / Standard	1.74	1.12	2.69	0.01
Positive reference / Negative c.	3.03	1.79	5.13	<0.001
Enhanced / Standard	1.09	0.65	1.81	0.98
Enhanced / Negative reference	1.89	1.05	3.42	0.03
Standard / Negative reference	1.74	0.98	3.09	0.62
				Intervals are backtransformed from the log scale

Crop leaf senescence

There were no differences in leaf senescence between the enhanced and standard treatments (p=0.48) Figure 3.3.

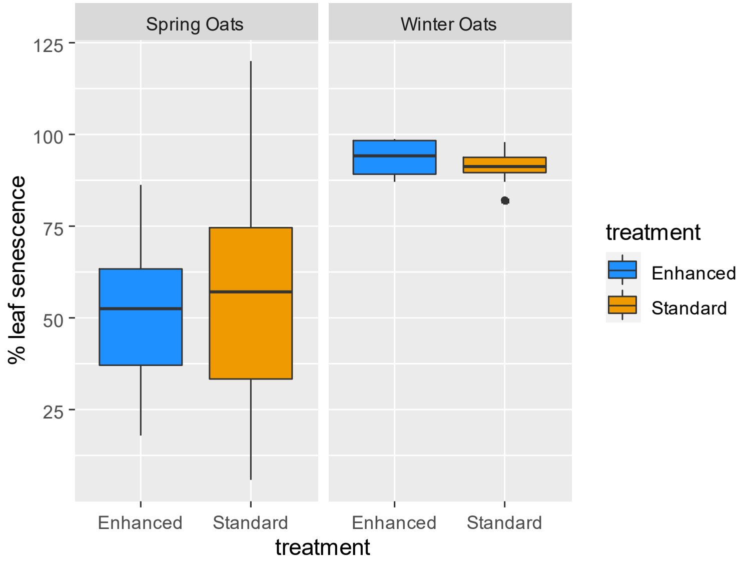

Figure 3.3 Leaf senescence %, boxplot median, interquartile range and 95% limit of data, by treatment and crop 2018

Soil aggregate stability to rapid wetting

Scoring of surface soil aggregate stability to rapid wetting, also known as the slake test, is shown in the plots in Figure 3.4.

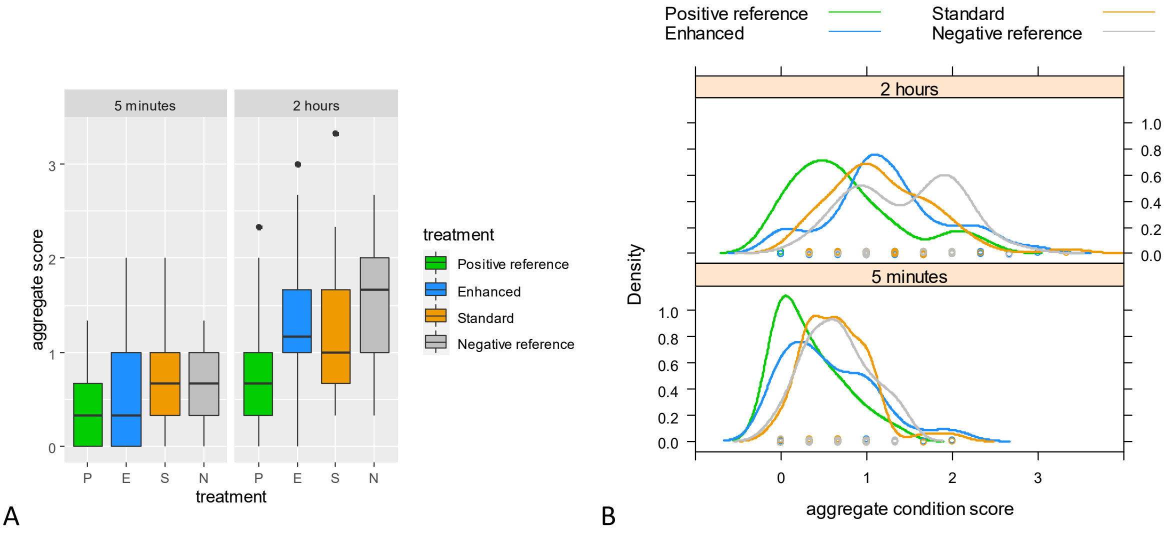

Figure 3.4 Soil stability to rapid wetting score, boxplot A assessment after 5mins and 2 hours, by treatment showing medians, interquartile ranges and data limits. Density plot B showing same data (lower score indicates more stable aggregates)

Overall, there was a very strong effect of treatment on soil aggregate stability (p=0.004), a strong effect was also observed of the duration of observation (p<0.001), predicted means and confidence intervals are shown in Table 3.3 (and Appendix Figure 3.6). There is a greater shift in the negative reference samples between the timed observations than with the standard or enhanced treatments (Figure 3.4B) however these were not statistically significant differences, Table 3.4.

Table 3.3 Soil aggregate stability scores, predicted means and 95% confidence intervals, by treatment and time lapsed

treatment	mean	Lower CI	Upper CI
			time = 5 minutes:
Positive reference	0.35	0.01	0.68
Enhanced	0.57	0.25	0.89
Standard	0.65	0.33	0.96
Negative reference	0.65	0.32	0.98
			time = 2 hours:
Positive reference	0.76	0.43	1.09
Enhanced	1.24	0.93	1.56
Standard	1.18	0.86	1.50
Negative reference	1.44	1.11	1.78

Positive reference indicates higher scoring at both times than all other treatments. The enhanced and standard were not different at either time, Table 3.4.

Table 3.4 Soil aggregate stability scores, contrasts of treatment pairs, by time lapse

contrast of treatment pairs	estimate	Lower CI	Upper CI	p-value
				time = 5 minutes:
Positive reference - Enhanced	-0.23	-0.61	0.16	0.429
Positive reference - Standard	-0.30	-0.69	0.09	0.182
Positive reference - Negative	-0.31	-0.73	0.12	0.236
Enhanced - Standard	-0.08	-0.43	0.27	0.937
Enhanced - Negative reference	-0.08	-0.47	0.31	0.943
Standard - Negative reference	-0.01	-0.40	0.38	1.000
				time = 2 hours:
Positive reference - Enhanced	-0.48	-0.87	-0.09	0.009
Positive reference - Standard	-0.42	-0.81	-0.03	0.029
Positive reference - Negative	-0.68	-1.11	-0.26	<0.001
Enhanced - Standard	0.06	-0.29	0.41	0.964
Enhanced - Negative reference	-0.20	-0.59	0.19	0.528
Standard - Negative reference	-0.26	-0.65	0.13	0.289

Weed burden

A large proportion of charlock (*Sinapis arvensis*), grass (Poaceae) and chicory (*Cichorium intybus*) counts were null observations, their respective Poisson mixed models thus did not converge and were not considered in treatment comparisons.

Weed above ground biomass

Biomass addition treatments did not influence the amount of fresh above ground biomass (p=0.73). There was no overall treatment effect on dry weed biomass (p=0.608).

Percentage visual weed assessments

Grass percentage ground cover overall treatment difference was not statistically significant (p=0.726). For total weed visual assessment, as percentage ground cover, there was no overall treatment difference (p=0.348).

Weed counts

The treatments did not influence the dock (*Rumex*) or dandelion (*Taraxacum officinale*) counts (p-value (*Rumex*) = 0.997, p-value (*Taraxacum officinale*) = 0.779).

The treatments did affect wild oat (*Avena*) counts (p<0.001), however, the p-values shown in Table 3.5, indicate the predicted means are not different from zero. Therefore, there is no scientific or indeed practical significance in the result.

Table 3.5 Wild oat counts.m^{-2}, predicted means 95% confidence intervals by treatment and p-values

treatment	rate	Lower CI	Upper CI	p-value
Enhanced	0.87	0.01	69.6	0.948
Standard	0.71	0.01	57.4	0.880

Discussion

This chapter tested four hypotheses relating to soil biota characteristics. These were retaining crop residues increases mesofauna numbers, reduces plant fungal load, increases soil aggregation, and reduces weed burden. Changes were considered relative to the standard treatment where crop residues are removed, and the two experimental references, a 5-year ley treatment (positive reference) and a routinely tilled fallow treatment (negative reference).

Mesofauna

Retaining above-ground crop residues increased total mesofauna counts by 33%. Returning leaf litter to the soil surface in the enhanced and positive reference treatments resulted in higher mesofauna counts compared to the standard treatment and the negative reference treatment. This confirms the connection between leaf litter and mesofauna numbers (Ostle et al. 2007, Briones 2014). This also confirms the importance of returning crop residues to the soil (Blanco-Canqui and Lal 2009, Powlson et al. 2011). This is important in both the contribution of SOM accumulation and the cycling of nutrients for feeding plants and other soil organisms (Thiele-Bruhn et al. 2012).

Collembola population expanded most in the positive reference. Some Collembola species are fungal feeders (Neher and Barbercheck 1998, Sabatini and Innocenti 2001, Mitschunas et al. 2008) and the lack of cultivation may have favoured their development in this respect. Collembola are also thought to transfer fungal and bacterial spores on their teguments to facilitate plant-soil microorganism symbioses (Klironomos and Moutoglis 1999) facilitating soil community development, which may have contributed to other beneficial developments in the positive reference.

Acari counts were highest in the enhanced treatment and both standard and positive reference gave higher counts than the negative reference. This may suggest a tolerance or even preference for a tilled environment, which coincides with their preference for the retained leaf litter (Scheu et al. 2005) in the enhanced treatment.

Despite the similar increase in numbers of mesofauna in the enhanced treatment compared to the positive reference, the enhanced treatment performed below the positive reference in other outcomes such as aggregate stability but also SOM and bulk density in Chapter 2. This could be due to the negative effect of tillage firstly on soil macro-aggregation (Burns and Davies 1986, Six et al. 2000) or secondly on other critical soil structure forming organisms, such as mycorrhizal fungi and earthworms and the reduced predation in that environment. The reduction in competitors for leaf litter food, as a result of tillage, would feedback to benefit the mesofauna in the enhanced treatment relatively. This fits with Tilman’s model for resource competition, where increases in diversity cause increases in community stability, but decrease in population stability (Tilman 1999). Here, in the enhanced treatment there is population increase and reduced diversity.

Crop leaf senescence

No change in leaf senescence was observed between the enhanced and standard treatments. It was hypothesised that adding biomass reduces pathogenic plant fungal burden. Mesofauna such as Collembola have been shown to consume pathogenic fungi (Sabatini and Innocenti 2001), its increase may therefore lead to increased leaf longevity. Such an effect was not demonstrated in this study, perhaps due to lack of pathogenic fungal activity in either treatment (which was not tested for). This is an interesting area of work and needs more attention in the future to aid cropping system development. The interaction of soil organisms with soil-borne plant pathogens is well documented (Neher and Barbercheck 1998, Janvier et al. 2007, Senechkin et al. 2014, van Bruggen 2015) and could provide increasingly valuable services in natural plant protection.

Soil aggregate stability

There was greater soil aggregate stability under rapid wetting in the positive reference treatment. In this case the soil was both left undisturbed for 4 years (assessment carried out in 2018) and had retained all crop residues. This favours the development of fungal hyphae (Chantigny et al. 1997) and other soil biota communities typically contributing to enhanced aggregation of soil particles (Tisdall and Oades 1982). SOM transformation is a biota-driven process through arbuscular mycorrhizal fungi, filamentous bacteria (Gougoulias 2014) and soil fauna such as earthworms (Six and Paustian 2014).

No difference between the other three treatments was observed. Two years of perennial diverse ley in the enhanced and standard did not have sufficient effect to make a difference over the negative reference. 5 years of perennial plants in the diverse ley was necessary to add sufficient above and below-ground biomass to improve soil aggregate stability to rapid wetting. This confirms the long-term advantage of perennial plants in improving soil function over annual cropping systems, which typically manifests itself as higher levels of soil fertility and structure and more complex biological communities (Culman et al. 2010, Asbjornsen et al. 2014). Döring et al. (2013) also found that diverse ley mixtures, relative to monoculture legume leys, improved ground cover, increases above-ground biomass, reduced weed biomass and increase biomass production stability. A relatively high level of SOM pre-experiment may have led to an optimal level of soil biota activity and contributed to the low aggregate stability scores even in the negative reference treatment. Indeed, the data indicates this may be the case, as very few soil aggregate scores of 3 or above (therefore indicating high aggregate stability generally) were recorded in any of the treatments (Figure 3.4B). Given that the scoring was carried out as part of a project looking at soil properties on many farms the results are not just subjective to this experiment.

Weed burden

Retaining crop residues did not change weed burden in this study. Chapter 4 looks at any yield effect between the two treatments. The results dismiss the hypothesis that retaining plant biomass reduces crop weed burden. Data from 1691 field trials of herbicides in Sweden showed weed biomass accounted for 31% of the yield loss due to weeds, with crop type (e.g. Spring barley being very susceptible to weed burden, then spring-wheat, oats, winter-wheat and rye being least susceptible) and geographic region accounting for most of the variation (Milberg and Hallgren 2004). This Swedish data also showed that in weed-free, or near weed-free trials, yield loss varied -/+20% indicating weed interactions are a complex phenomenon. The weed seedbank can be affected by predation of seeds (Honek et al. 2003) by different species including, macrofauna, mammals and birds. Seeds can also be affected by meso- and microorganisms (Chee-Sanford et al. 2006, Mitschunas et al. 2008). All these soil organisms can in turn be affected by biomass addition (Gallandt et al. 1998, Fennimore and Jackson 2003). Weed control is a critical element to all farming systems, though organic farming is more limited as to its remedies, therefore, any methods that demonstrate fewer weeds might be important for the profitability of these systems (see Chapter 4).

At the same time, weeds provide an important source of food for many organisms, including pollinating insects and in turn farmland birds feeding on insects (Marshall et al. 2003, Bretagnolle and Gaba 2015), also through increased plant root community dynamic, facilitating increased soil development (Mueller et al. 2013). In some cases, diverse and non-competitive weeds can be beneficial for wildlife with little impact on yield (Adeux et al. 2019). This study found no change in weed burden from increased biomass addition.

Conclusion

Comparison of enhanced and standard treatments, regarding soil biota outcomes, has yielded a change in biodiversity composition for retaining biomass. Total mesofauna numbers increased, particularly Acari, which can lead to improved nutrient supply.

Collembola were responsive to retention of crop residues compared to the fallow treatment-plots and are important as they can provide fungal pathogen control for plants. Chapter 4 explores if these factors have any crop yield interactions.

Weed burden did not change with retaining crop residues.

Only the positive reference had an improved soil aggregate stability, these follow the soil function benefits found in Chapter 2. Soil aggregate stability has a positive impact on soil structure, water holding capacity, SOM protection, ease of soil tillage and ultimately on yield. This study can recommend to all land managers the improved soil function accruing from ley farming with diverse species mixtures.

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Appendix of plots of predicted means and 95% confidence intervals

Mesofauna

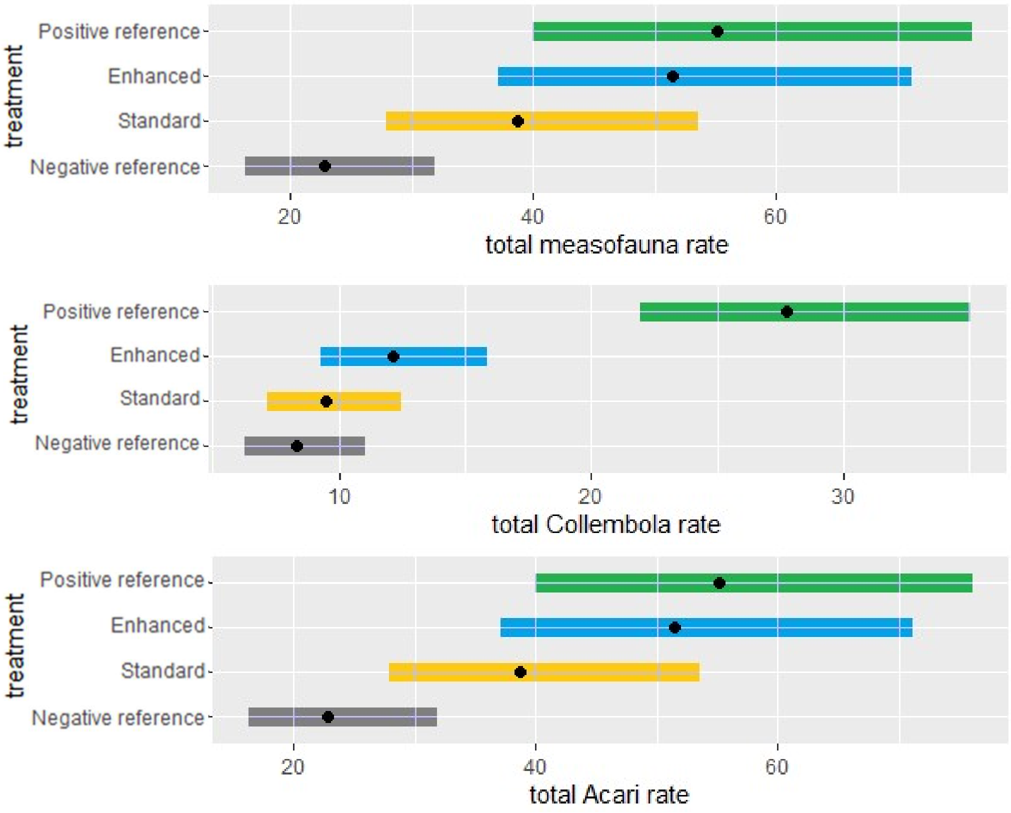

Figure 3.5 Total mesofauna, Acari and Collembola counts, plot of predicted means in three graphs, by treatment, with 95% confidence intervals

Soil aggregate stability

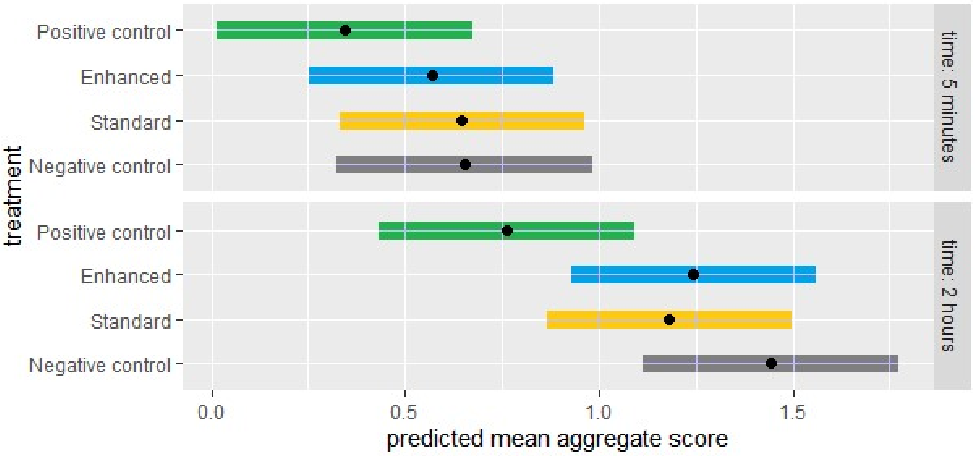

Figure 3.6 Soil Stability to rapid wetting, plot of predicted mean scores and 95% confidence intervals, for 5 min and 2 hr assessments, by treatment

Chapter 4. Crop Value

Introduction

Current challenges in the global food system could be (partially) mitigated by organic production systems

Global food production systems face immediate and proximal challenges, including yield stagnation with an expanding population (Grassini et al. 2013), biodiversity loss (Dasgupta 2021), soil degradation (Borrelli et al. 2017) and climate change (Altieri et al. 2015).

Organic agriculture can offer positive solutions. Organic systems combine a traditional conservation-minded approach with modern technologies and techniques (Reganold and Wachter 2016). They can improve biodiversity (Tuomisto et al. 2012), increase profitability (Seufert et al. 2012), use diversity of crops and animals (Mader et al. 2002), reduce energy use per unit of production, reduce nutrient losses, and enhance soil organic matter (Gattinger et al. 2012, Tuomisto et al. 2012).

The main criticism of organic farming systems is their lower yield per unit area, compared to conventional systems (de Ponti et al. 2012, Seufert et al. 2012, Röös et al. 2018). It has been suggested that more land might therefore be needed if a wholesale switch to organic farming were to take place in the UK (Smith et al. 2019). However, given the current state of biodiversity, soil degradation, pollution, and risk of disease epidemic, it is questionable that agriculture can risk the continuation of the current conventional farming model (Tilman et al. (2011). In the meantime, improvements to the organic and broader agroecological methods are being explored and the yield gap researched (Caldbeck 2016).

Approaches to address productivity challenges in organic systems

Organic systems focus on soil improvements to enhance crop production, mainly through increasing the amount of soil organic matter (Watson et al. 2002). Soil organic matter (SOM) cycles and stores nutrients, stores water, allows plant root access to soil, and is a food source for biota that mitigate pests and diseases (Neher and Barbercheck 1998). Nitrogen, a key plant nutrient, is introduced to organic systems by growing legumes which biologically fix nitrogen from the atmosphere. Plant nitrogen and carbon enter soil as SOM by one of two routes. Firstly, after being metabolised by soil fauna or mammals and excreted. Secondly as biota necromass, such as glycoproteins from arbuscular mycorrhizal fungi and filamentous bacteria whose necromass glues soil particles together (Gougoulias 2014). This has important benefits for soil aggregation and structure.

Organic techniques aim to enhance these processes by using diverse plant and animal communities, growing pasture leys, returning crop residues to the soil, and grazing animals on the pasture - otherwise known as traditional mixed farming (Mader et al. 2002, Reeder and Schuman 2002, Machmuller et al. 2015). Using diverse mixtures of legume-based ley pastures can combine the benefits of legumes and diversity and improve soil fertility for subsequent crops (Döring et al. 2013). Deep rooting diverse ley species can also access phosphorus with the aid of fungal associations (Leake et al. 2004, Cameron et al. 2013). Diversity can be achieved through rotation, in an 8-year crop rotation experiment in Canada, Malhi and Lemke (2007) report increased yield of barley, wheat, and pea crops when retaining crop residues.

SOM content of the soil is driven by several concurrent processes, such as inputs of organic matter, soil biota activity, chemical and biological stabilisation, and physical protection from degradation (in clay and fine silt textured soils) (Edwards and Bremner 1967, Tisdall and Oades 1982). Time is the main limitation to these complex soil systems. SOM accumulation and the improvement of soil condition accrue over long periods (Machmuller et al. 2015). Tillage can mineralise soil organic matter, making nutrients available to plants in the short term but reducing the long-term potential carbon sequestration. Reduced tillage can improve soil properties such as water infiltration and bulk density, but not affect carbon sequestration (Blanco-Canqui and Lal 2008).

Off-farm inputs are generally unsustainable

Productivity improvements in organic farming systems are often made using additional off-farm inputs such as animal manures, anaerobic digestate, organic fertilisers, or other permitted inputs and supplements such as seaweed (Watson et al. 2002, Niggli U 2016, Röös et al. 2018). Off-farm inputs can provide a way of recycling nutrients from outside into organic farming systems to manage off-take of nutrients from crop sales (Watson et al. 2002). However, if organic farming is to be one of the truly sustainable solutions to food production (Pretty 1994), then improvements to yield have to be within the capabilities of the farm. Obtaining input from beyond the farm opens the farm to the uncertainty of a cross-subsidy from a different ecosystem, and the possibilities of unknown externalities, such as trade disruption, natural resource depletion, or pollution (McIntyre et al. 2009). In a carbon sequestration context, discussed in Chapter 2, off farm inputs of carbon for improving soil would be a transfer of carbon from one location to another and therefore not deliver climate mitigation (Poulton et al. 2018). By this reasoning, inputs from outside must be viewed as non-systemic solution.

Producing on-farm inputs reduces the risk of importing hazards to health in the farm system. If farmers could adopt a more closed farm approach by producing their crop fertility inputs on-farm, they would become more self-sufficient, more sustainable, reduce their costs and be less susceptible to external shocks (Schiere et al. 2002, Tilman et al. 2002).

Biomass quality

Whilst retaining crop residues within the field or the farm is desirable from the sustainability point of view, it is widely understood by farmers that adding cereal crop residues to the soil will reduce the nitrogen available for the following crops and will thereby reduce crop yields in nutrient-limited systems (Dunn 2006, Schmidt 1997) as cited in (Heijden et al. 2008). In this situation, soil microbes are thought to use limited available N to digest crop residues that have high C:N ratios, therefore reducing the N available for plants (Scheu et al. 2005).

Low C:N ratio residues can alleviate this issue and increase retention of carbon and nitrogen in soils. This increases sustainability, reduces pollution (Drinkwater et al. 1998), and feeds soil microbes that can produce high N faecal pellets available to plants (Frouz 2018). Soil microbe diversity is directly affected by plant residue diversity and quality (Scheu et al. 2005). Variation in residue quality will therefore affect energy available for microbes to digest organic matter, this is referred to as the thermodynamic factor of organic matter dynamics and degradation (Bosatta and Ågren 1999). Bhogal et al. (2009) found that it took relatively large quantities (up to 65 t Organic Carbon ha^{-1}) of crop residues to affect soil properties, they suggested these are therefore likely to result in long-term yield benefits. A diverse range of residues can have benefits for following crop demands and reduced leaching of nutrients (Handayanto et al. 1997, Watson et al. 2002). A review of impacts of residue removal on crop yields finds they are highly variable, depend on the tillage method, cropping systems, duration of tillage, crop management, soil-specific characteristics (e.g., texture and drainage), topography, and climate during the growing season (Blanco-Canqui and Lal 2009).

There are knowledge gaps regarding the question of the economic value of feeding the soil with in-situ grown plant material (biomass) in both short- and long-term situations with the aim of increasing crop productivity. There is also compelling need to address the yield gap in organic compared to conventional agricultural systems (de Ponti et al. 2012, Seufert and Ramankutty 2017). The research presented in this chapter aims to identify an improved method of crop production in organic systems that enhances crop value whilst minimising farm environmental and financial costs. A replicated experiment was set up on-farm to investigate the effect of increased biomass input to the soil over five years (2014-2019), by returning crop residues to the soil and incorporating additional cover crops. The objective of this chapter is firstly to look at the yield and quality of the crops grown on the experimental treatment-plots, secondly, to explore the cost-benefit to the farm of returning biomass to the soil rather than selling it off-farm.

This chapter tests the following hypotheses:

1. Retaining crop residues increases crop yield and reduces variability in yield: Tested by combine yield; yield by hand; and crop establishment counts.
2. Retaining crop residues increases crop quality: Tested by grain characteristics including hectolitre weight; and forage quality brix test.

Changes will be considered relative to the standard biomass input treatment where crop residues are removed. To make the research findings directly relevant to current agricultural practice all plot work is carried out by existing farm equipment.

Methodology

Site description and Experimental Design

These are detailed in Chapter 2

Investigations and sampling protocols

Yield assessments of plots were taken as whole-plot samples by the combine harvester and by within-plot sampling by hand. Within-plot assessments of yield and quality were measured at four sampling sites within each of the two treatment-plots (enhanced, standard). The location of within-plot sampling sites was determined by using a stratified random approach by first splitting each full-size-plot into quarters, then randomly generating coordinates for one sampling site per quarter. This resulted in 4 sampling sites per treatment-plot, 24 per field, and 96 across the whole farm. Biomass quantity samples from a one metre square area were taken at each sampling site: collected, weighed, and stored inside, air-dried for several weeks, and turned to ensure thorough drying. The samples were then weighed again, and weights were recorded. Sugar content was assessed using a Brix meter on 6th August 2018: 10 leaf samples were collected randomly within a one-metre quadrat at each sampling site. Leaf samples were squeezed using a garlic crusher to obtain the juice; this was placed on the reading screen and the value viewed from the Brix refractometer was recorded (Marigheto et al. 2006). The Brix test uses light refraction to assess the sugar content of the solution produced from the liquid in leaves and is being more and more widely used as a tool by farmers to assess crop quality (James 2018). Hand harvesting for crop quality was carried out at each sampling site using a one metre square plot, from where all the seed heads were removed and stored in paper bags. The bag contents were then weighed and air-dried. The samples were reweighed, threshed, winnowed, weighed to obtain a hand-harvested weight. A Perten model DA 7250 near-infrared spectroscopy (NIR) analyser was then used to assess the quality characteristics recorded (grain moisture, protein dry basis, ash dry basis, fat dry basis, fibre dry basis, NDF (neutral detergent fibre). A standardized 15% moisture content sample weight was calculated using the hand grain sample moisture. A hectolitre grain weight was measured by weighing a known volume of grain. Crop population in the Spring was measured at each sampling site, counting the number of plants in a one metre square. Plot-level yield mass from the combine harvester was recorded by first cutting around the perimeter of the plots and discarding. The treatment-plots could then be harvested without any standing crop surrounding the perimeter, thus avoiding contamination with grain growing on the outside of the plot. The full combine header cutter width was taken for the full length of the plot and the quantity harvested recorded from the combine RDS yield meter. Combinable crops were only planted in the enhanced and standard biomass input plots (reference-plots will not feature in these results).

Statistical analysis

Data was validated for completeness and boxplots of all variables were used to identify extreme values and explore the distribution of the data. To account for the pseudo replication that resulted from the stratified random approach to sampling, these results are analysed using a nested mixed model with treatment-plot nested in replicate and replicate nested in field (1|field/replicate/treatment-plot). Therefore, mixed models were used to analyse all the responses, with a support distribution as required by statistical modelling for each outcome, namely: Normal; Lognormal; Poisson; Beta (Brown 2015). A Normal distribution was used to model the Brix reading by treatment. Plot-scale combine harvester yields were modelled using a normal distribution using random effect of field and fixed effect of crop, then again for year instead of crop. Beta distributions were used to model five measures of crop quality assessment, expressed as percentages with no denominator. A Normal distribution was used to model dry grain yield and hectolitre weight. Counts of crop populations were modelled using a Lognormal distribution by treatment and crop, due to large counts (the Poisson distribution was not used as the Normal distribution is a good approximation to the Poisson when the mean is large and there are no zeros, a true Poisson has a different variance to the population seen here). In interpreting the results some statistically significant results are shown to be of such small effect, considering the units used, to be of no practical importance, these are noted. P-values of less than 0.05 were deemed indicative of statistically significant effects. The data was analysed and modelled in R, version 4.1.0. The denominator degrees of freedom were computed by the Kenward-Roger method.

Results

Plot yield

Results from the combine harvester varied by crop and year, as shown in Figure 4.1 below.

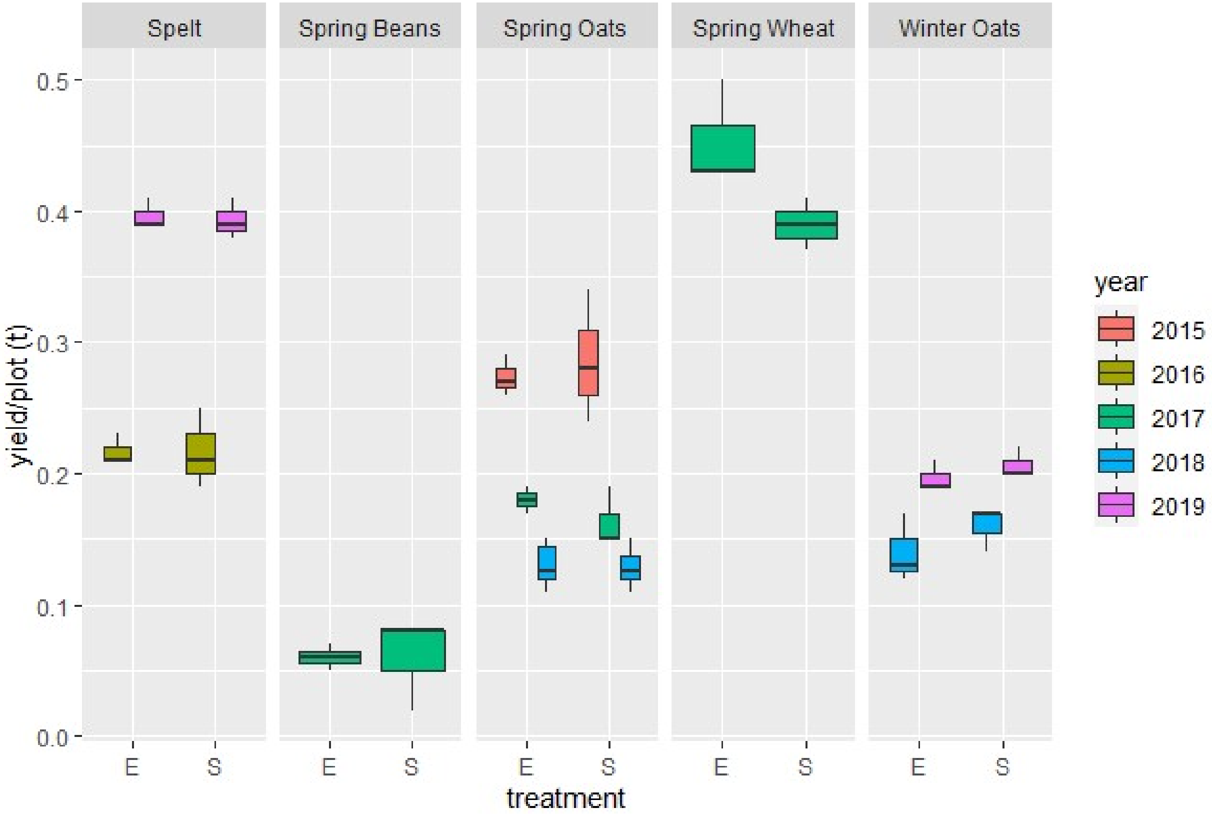

Figure 4.1 Combine Harvester yields (t/plot), boxplot at 15% moisture, by crop, year as treatment pairs showing medians as black bars, boxes as interquartile range and lines as 95% limit, E-enhanced, S-standard

There was no difference between treatments in yield per plot, either for crop effect (p=0.56), or for year (p=0.86), but results may be misleading due to interacting of crop with year. Looking at the data Spring wheat in 2017 gave a higher yield in the enhanced; whereas Winter oats in 2018 and 2019 gave a lower yield in the enhanced treatment.

Hand-harvested grain assessments

Assessments of grain quality were carried out on oats harvested in 2018. Results are presented in Figure 4.2.

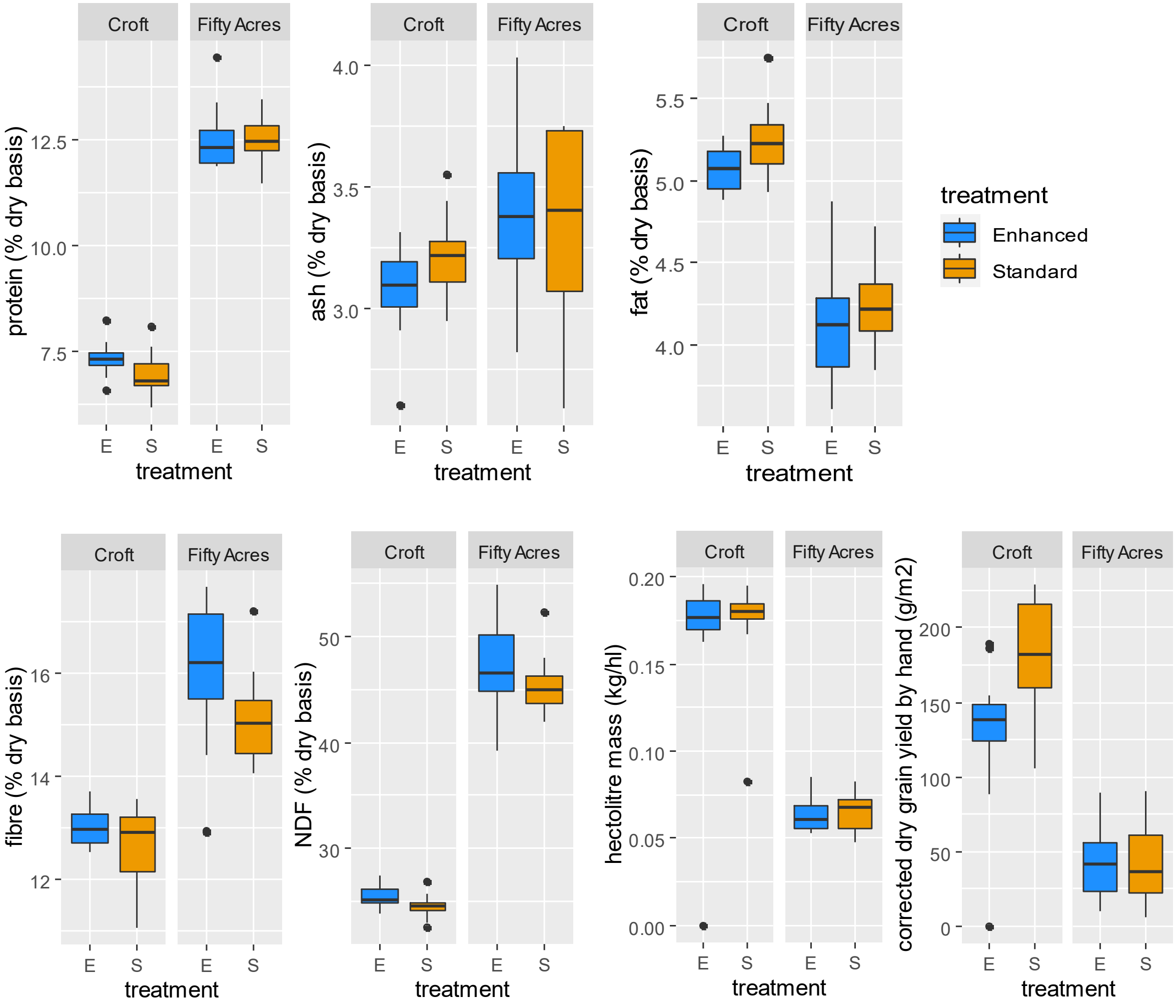

Figure 4.2 NIRS five quality assessments, plus hectolitre and corrected hand grain yield, boxplots, showing median, interquartile range and 95% data limits

There were no differences between enhanced and standard treatments for any of the grain quality assessments (p-values: protein=0.99; ash=0.418; fat model did not converge; fibre=0.686; neutral detergent fibre=0.377; corrected grain yield=0.111; hectolitre weight=0.55).

Crop population counted in Spring

Assessment of crop population is shown in Figure 4.3. There was no overall treatment effect (p=0.93).

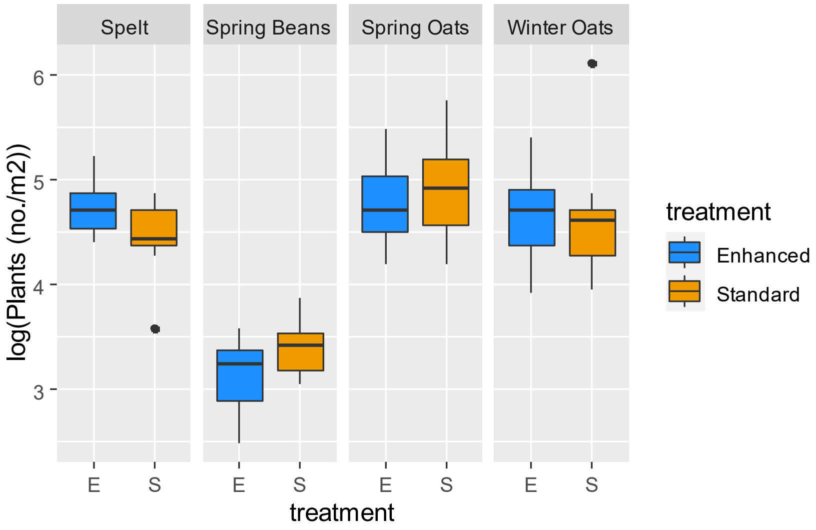

Figure 4.3 Crop population log(plants/m2)), boxplot by crop and by treatment, spelt was Winter sown

Leaf sugar content

There was no difference between the treatments for leaf sugar content in Spring field beans in 2018, as measured by the Brix test (p=0.49; figure 4.4), (E-S effect measure 0.05, 95% CI -0.218 to 0.322).

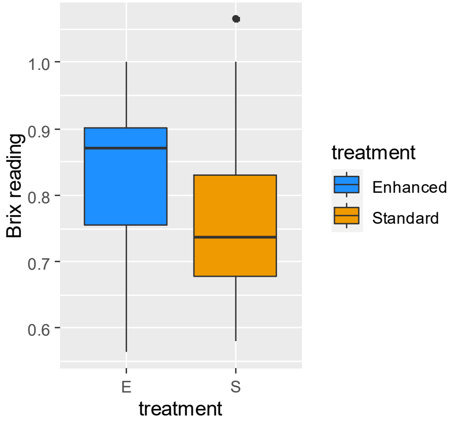

Figure 4.4 Leaf sugar test, boxplot 2018 results, by treatment, showing median, interquartile range and limits of data

Discussion

There was no change to yield, quality of crops or establishment rate between the enhanced biomass input plots where crop residues were retained and the standard biomass input plots where they were removed. These results do not support the hypotheses that adding in situ grown biomass (retaining crop residues) improves the crop yield or its quality.

Retaining crop residues from the combinable crops

In contrast to the above hypothesis of increased yield from adding biomass, current farmers' understanding, which has been attained from meetings and information from farm advisers, is that adding biomass in the form of crop residues to the soil will reduce plant-available nitrogen (N) and reduce crop yield where nutrients are limiting, which is supported by experimental data (Dunn et al. 2006, Heijden et al. 2008, Smith and Read 2010). On this basis, farmers would expect the enhanced treatment to give a lower yield than the standard. The advice has been so strong that in September 2019 a farmer reported that he was adding nitrate fertiliser in Autumn to help microbes digest straw residues. Nitrate fertiliser applied in Autumn is likely to be leached as plants will not be actively growing to take it up. Rather than nitrate fertiliser, research in the US shows leafy residues from cover crops (green manures) such as radish and Winter peas with low C:N ratios (Jahanzad et al. 2016) could provide the thermodynamic factor (Bosatta and Ågren 1999) to prime soil organisms to decompose crop residues (Frouz 2018). Interestingly, where yield was not limited by nutrient availability, a 17-year experiment at Rothamsted, UK, tested the incorporation of cereal straw residues rather than burning them and found no measurable increase in %C either with ploughing or non-inversion tillage (Johnston et al. 2009).

Crops residues can impede crop establishment by blocking seed drill coulters and also provide a favourable habitat for slugs (Christian and Miller 1986). The close proximity of crop residues to the seed can affect emergence (Shipton and Tweedie, 1967; Ellis et al., 1975; Graham et al., 1985) as cited in (Guerif et al. 2001). Crop residue decomposition under anaerobic conditions can also give rise to toxic leachates which can injure the seedling (McCalla and Haskins, 1964; Kimber, 1967; Patrick, 1971; Lynch, 1977, 1978) as cited in (Guerif et al. 2001). The study in this chapter did not find any change in crop establishment with residue retention. It is likely after many years of working with crop residues and without ploughing at the experiment site both the farm system and the soil have already adapted to retaining crop residues (see similarity between enhanced and standard below).

Retaining crop residues from the diverse ley

The enhanced treatment-plots have also received more biomass input to the soil than the standard through crop residue retention during the diverse ley phase of the rotation. Both enhanced and standard treatments had two of the five years of the experiment under diverse ley, with the above-ground biomass in the enhanced being returned to the soil surface. The retained material is likely to have had a low C:N ratio (Bending and Turner 2009), which in turn would have a high thermodynamic factor, meaning it has energy highly available for metabolism by soil organisms (Bosatta and Ågren 1999, Lehmann and Kleber 2015); indeed priming soil organisms to decompose crop residues (Frouz 2018).

The low C:N ratio would be partly from the grass and legume diversity in the diverse ley mix (Birkhofer et al. 2011) and partly due to improved root dynamics (Mueller et al. 2013). Mueller et al. (2013) found in their 12-year experiment that diverse plant communities had greater root development than would be expected from monoculture comparisons, with the expectation of greater foraging potential by roots leading to improved nutrient status for the plants.

Chapter 3 has shown that there is sufficient biomass being returned to the soil in the enhanced treatment to increase mesofauna, particularly Acari, compared to the standard treatment. However, there was no knock-on effect in the enhanced treatment compared to the standard, in this same experiment, in terms of SOM, bulk density or aggregate stability (see Chapters 2 and 3 for further details), or indeed crop yield or quality. Similar results were found by Bhogal et al. (2009). The increased mesofauna produce excreta from having processed the plant litter or consumed other soil microbes, which will be available to feed plants (Frouz 2018), but no evidence for improvement in plant quality or yield was found in this experiment. Does the plant material lying on the soil surface oxidise and not reach the soil? This is unlikely as there was an effect of increase in mesofauna numbers implying leaf litter reaching the soil and being metabolised by these mesofauna. There is perhaps a lag in the system where the diverse ley residues have improved mesofauna numbers but there has not been enough time to pass on the benefits into subsequent crop growth (Bhogal et al. 2009).

Residue quality

There was no subsequent reduction in yield. Yield reduction might have been expected from previous research (Dunn et al. 2006, Heijden et al. 2008, Smith and Read 2010); due to the addition of crop residues in the enhanced vis-à-vis the standard treatment. The plant residues in the enhanced treatment are likely to comprise a mixture of high N residues from the ley phase, and low

N residues from the cereal straw residues, in terms of C:N ratios over the course of the 5 years. The crop residues in the diverse ley phase of the enhanced treatment may therefore be providing the N in low C:N residues needed to break down the C-rich crop residues of the combinable crop phase. The residues from the diverse ley and the residues from the combinable crops have apparently reached an equilibrium of C:N ratios that had nil effect on yield and quality. But they did lead to biodiversity gain found in Chapter 3. Namely increases in mesofauna.

Similarity between the enhanced and standard treatments is greater than the difference

The standard and enhanced treatments in this experiment are similar relative to arable systems and perhaps share influential positive root traits. Both treatments have high crop diversity and a two-year ley, differing only in the use of above-ground biomass.

Root exudates from the ley plants, in both treatments (and the positive reference seen in the other chapters), can comprise up to 21% of the total carbon fixed by photosynthesis (Hütsch et al. 2002, Jones et al. 2004, Mendes et al. 2011), which could contribute to subsequent crop yields, for example through the activity of mesofauna seen in Chapter 3 and the cycling of soil organic matter shown to accumulate in Chapter 2. Root inputs were found to have on average 8.1 times the effect on SOM stabilisation as the same amount of above ground biomass, in a review of agricultural field studies of different cropping systems by Jackson et al. (2017).

Further to this, after over 10 years of working with diverse leys over the whole farm prior to the experiment, the soils may have already adapted to higher levels of biomass input (Mader et al. 2002, Fliessbach et al. 2007, Döring et al. 2013). This is demonstrated by the improvement of SOM on the farm outside the treatment-plots, over the past twenty years with approximate increase of 2.2 $g.kg^{-1}$ SOM per annum.

Yield variation by year

Variation in yield by year can be due to climate, rotation, location, weeds, pests or crop combination (Milberg and Hallgren 2004). Although the statistical model gave a p-value of 0.86 for variation of yield by year, this was confounded by crop effect and there was insufficient data to explored individual crop yield variation by year.

Opportunity cost

Concerning economics, there was no statistical difference in yield or quality as a result of retaining crop residues. Therefore, there was no benefit to set against the opportunity cost of not selling the removed biomass (Lockeretz 1981). Despite increased biodiversity in soil mesofauna counts being measured after retaining crop residues in Chapter 3.

However, soil measurements presented in Chapter 2 found both the enhanced and standard treatment increased SOM over the 5-year study. These changes are likely to lead to improved soil physical, chemical and biological properties (Fageria 2012): improved availability of nutrients, improved water holding capacity which means greater tolerance of flood and drought (Dwyer et al. 2015), and increased biodiversity (Thiele-Bruhn et al. 2012).

Further benefits were measured from increased biomass addition in the positive reference in the 5-year ley: increased aggregate stability, reduced bulk density and higher SOM. These soil function improvements in the positive reference could materialise in the 2-year ley rotation over longer time periods and these soil functions are of considerable benefit to farmers, to society, and to climate change mitigation (Dwyer et al. 2015, Lange et al. 2015, Bossio et al. 2020).

Although these benefits are difficult to monetarise, they are no less important (Dasgupta 2021). Indications are from the current Agriculture Act 2020 that there will be UK government payments to land managers to produce public goods, such as environmental improvements (Finlay et al. 2021).

Conclusion

The crop yield and quality were not changed by retaining crop residues in the enhanced treatment. The increase in mesofauna found in Chapter 3 did not lead to increased yield during this 5-year study. Further research is urgently needed in this area to address the yield gap between organic temperate climate cropping systems and conventional crop yields, to cement the benefits that arise from organic farming systems such as increased soil organic matter (Gattinger et al. 2012), improved biodiversity (Tuomisto et al. 2012) and profitability (Seufert et al. 2012).

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Chapter 5. Feeding the soil, benefit to soil and farm homeostasis

Introduction

The objective of this chapter is to share a passion for soil. Through the combination of existing knowledge and the findings of this doctoral research, its vital usefulness can be shared with others including farmers, growers and gardeners, farm consultants and advisers, the public and government. Communicating the importance and value of soil has never been more urgent. The global soil wealth is greatly depleted (Bai et al. 2008), largely due to anthropogenic factors, with over exploitative farming practices chief among them (Montgomery 2007, Bonanomi et al. 2016). Every person can engage in improving this situation, by adopting gardening or farming techniques that are beneficial to soil (regenerating soil function) or by simply choosing to buy foods and fibres produced in systems that are soil friendly. Farmers have an ability and a responsibility as occupiers and custodians of the land to protect and enhance the soil. Soil is a living, breathing entity which must be respected and nurtured to continue providing its invaluable functions that every citizen relies upon every day. These functions include food production, water storage and flood prevention, nutrient storage and cycling, harbouring wildlife and biodiversity, and carbon sequestration and pooling. The soil is multi-talented and multifunctional.

This chapter discusses, how this research demonstrates that land managers can use the scientific method to their advantage, how to engage with farmers in this context of the dynamic nature of soil, what benefits farmers can accrue from this in terms of resilience and homeostasis and cropping systems recommendations from this research.

1. Science and farming

Robust farm experimentation using existing farm machinery is feasible and can produce dependable outputs that farmers can use directly and share with their colleagues. In farming circles questions often arise about the appropriateness of applying science in farming, indeed whether science really applies in a farm situation. Recently, in answer to a question posed to a progressive farmer, the response was “I don’t think science really works in the field” and with regard to measuring soil organic matter “…there are too many tests and variabilities between them to make the tests worthwhile”. Stockdale and Watson (2012) indicate there was little critical engagement between researchers and farmers/advisors working in soil biota development in 2012. With specific regard to SOM, there are several ways to measure SOM. Loss on ignition is the most widely used, but different laboratories often use different temperatures. At higher temperatures in clay soils tightly bound water can be released and similarly calcium carbonate can be oxidised both giving variable SOM results (Howard and Howard 1990, Hoogsteen et al. 2015, NRM 2019). As shown in Chapter 3, some variation in SOM testing is to be expected. It is important to rigorously document methodologies which may aid future comparisons and explain inconsistent results.

When the journey of agricultural adaptation started at the experimental site at Yatesbury in the 1990s, there were some limited SOM measurements taken across the whole farm. This was thanks to the Organic Research Centre's suggestion, but the cost was prohibitive. Thanks to that data it is possible to demonstrate the enormous impact that the alternative methods have enabled. The farm system is still constantly being challenged and, as Chaney (2017) says, the search for innovations that improve profitability, stewardship and quality of life continues. This doctoral research and literature review has opened up the value of science to demonstrate the individual, contributing factors in any system, to help to explain complexity. Whilst always having in mind the assumptions that are made in the scientific method and how these can affect the results, always looking for the hidden interactions and influences, for example the temperature at which loss on ignition SOM analysis is conducted.

Farmer interest in in-field on-farm research has intensified in recent years. Initiatives such as the Innovative Farmers (MacMillan and Benton 2014) and the ADAS Yield Enhancement Network (www.yen.adas.co.uk) have inspired farmers to come together and experiment to answer questions that are concerning them on-farm. The advent of GPS technology has provided farmers with the means to conduct comparisons of inputs on-farm at a simple and inviting level (ADAS 2018). Experience shows that the majority of farmers still conduct their on-farm comparisons in a way that does not produce robust results: results being non-reproduceable; not applicable beyond the field and situation they originate from. With a little more structure, guidance and discipline, farmers could easily conduct experimentation that follows the scientific method, making their results relevant for a much wider audience. The biggest challenge to the application of scientific methodology is the use of statistics. As a doctoral researcher, with access to supervisors and to a statistical service department, the experimental set up and data analysis becomes more routine. Appropriate experimental design and statistical analysis is a critical part of the scientific method and is where many farm comparisons fall short, the lack of a control or the lack of replication are examples of this. The best way to ensure statistical validation is to cooperate with a professional researcher. They will have the experience necessary to validate the experiment. The Innovative

Farmers project is a great example of this approach, funded by the Duchy Originals brand, farmers that share a common research interest are partnered with an appropriate researcher to set up an on-farm experiment to answer the group's question (MacMillan and Benton 2014).

1.1 **This experience of on-farm research**

The research question came about because of encouragement by other long-term organic farmers to feed as much crop residues or green manures to soils as possible and a question as to the actual consequences of adopting this approach had arisen. Returning crop residues to the soil, rather than selling them off farm for mushroom compost or animal bedding has a clear loss of revenue implication. While there had been anecdotal improvements in the soil function from such practices at Yatesbury; hard evidence was missing of what positive (or negative) quantifiable outcomes there might be.

The experiment was set up across the farm in four different fields with different soil types and with different weed pressures. The fields were also at different points of the rotation giving a space for time experimental design. Given that the full farm rotation was seven years and the experiment five years, by using different fields across the rotation the whole rotation could effectively be covered. This is known as a space for time substitution (Pickett 1989)**.** To simplify the management of the experimental plots, for example without having to rely on an external combine harvester for small plot scale plot harvesting, the plots were designed to work with all the existing farm machinery. The experiment was designed to test the performance of an enhanced biomass input rotation (in-field retention of crop residues and winter cover crops), in comparison to a standard biomass input rotation (crop residues are removed and sold off-farm). Reference plots were also established to facilitate comparisons between the fields. The reference plots were split in half with a positive reference (diverse ley (ley = short term pasture) representing maximum C input) and negative control (all plant growth deterred by routine tillage 3 times per annum, representing a minimum carbon, starvation of soil biota), constant in both over the 5 years. Three replicates of all the plots were established in each of the four fields. The plots were positioned randomly within each replicate (see Chapter 2, Figure 2.1). The treatment-plot cropping followed the cropping in the surrounding field which made managing the cultivating of the plants in the plots routine. This style of design lends itself to in-field experimentation by other farmers.

Over the six years that this experiment has been planned and run, a great deal has been learnt and many mistakes made. Further advice and references on setting up farm trials are detailed in this Appendix. Management of the plots was considered routine as the plot operations did largely fit with the surrounding field work. At a fundamental level, permanent marking of the plots was difficult initially as large machines would often remove or damage the plot markers. As a solution, permanent (tree) stakes were used around the reference plots which were less disturbed, with temporary (cane) markers around the treatment plots, this allowed for more flexibility whilst having a permanent guide for the temporary markers. Sample taking and observation recording was sometimes a challenging aspect of the research, not only from the attacks of horse flies, but because it was very labour intensive and required help from outside the farm. On many occasions support was received from students from UoR and other universities, though they were not always reliable, some did not arrive while others had to leave due to poor health, yet others were exceptionally helpful. Dealing with the data required an organised system and good student discipline. Even so, the benefits of a robust experimental process far outweigh any challenges as can be seen from the results presented in previous chapters.

1.2 **Engaging other farmers to adapt to inevitable generic change**

Many farmers have visited Yatesbury farm and been introduced to the experiment. This has been one of the great benefits of setting the experiment on a working farm. Discussions with farmers and researchers have aimed to find the barriers that farmers have in doing their own research, what interests them about this research approach or other approaches, and whether they are now more interested in carrying out their own research in this format. Perhaps more importantly: What is it that inhibits adaptation even though, given time, change is inevitable (Sutherland et al. 2012, Mase et al. 2017)?

In farming, the only certainty is the constant change of the status quo. There are many stresses, generally external, which result practically in system adaptations. These stresses range widely from economic pressures, such as trade, subsidies and development, to biotic pressures such as invasive species, pests or biodiversity loss. They include social stresses such as ageing, succession and peer pressure, also human population growth and global events such as pandemics or climate change. All these stresses have been endured before and it is human adaptability that ensures human survival and means humans have moved on from being troglodytes.

The scientific method delivers probabilities of outcomes, and this concept can be difficult to explain to a farming audience. As Pretty (1994) describes “The trouble with normal science is that it gives credibility to opinion only when it is defined in scientific language, which may be inadequate for describing the complex and changing experiences of farmers and other actors in rural development. As a result, it has alienated many of them.” This highlights that it is the way ideas or new methods are presented that sparks the interest in that idea to a person. Often a practical approach connects with practical people. It was the passion of other organic and biodynamic farmers that encouraged adaption at Yatesbury in the 1990s, rather than any strength in the organic market. Inspiration came from pioneers such as Ian Tolhurst, David Wilson, John Newman, Tim and Jo Budden, Adrian Steele, Barry and Nigel Wookey, Manfred and Fredrick Wenz but particularly Alex Podolinsky.

Engaging farmers in the process of adaptation can be difficult (Sutherland et al. 2012), even when clear scientific evidence is available to demonstrate the benefits of a new system or technique. One approach to encourage adaptation in farmers has been through small incremental moves such as those in the Common Agricultural Policy’s Environmental Stewardship schemes (Sutherland et al. 2012). However Sutherland et al. (2012) explain this has not been successful because of the limited active involvement in prescriptions of the scheme such as leaving hedges untrimmed or leaving a field margin uncultivated. Farmers did not need to engage in why they were making these adaptations. The adaptations were simply tick boxes to collect a subsidy. The interventions are often carried out without realising the end goal and understanding the change envisaged.

Another approach to change, the motivational interviewing technique, was developed by Carl Rogers in the field of medicine to encourage people to live healthier lives. It works by persuading people that they have changed already, by discussing what is current practice and picking appropriate indicators of positive action: a process of affirmation (Miller and Rollnick 2004, Rollnick 2018). An excuse often heard against adaptation in farming circles, given by farmers seeing new systems or techniques, is that it won't work on my farm/soil/location. Economists call this lock-in or path dependency (Sutherland et al. 2012). When receiving visitors to Yatesbury farm, it is sometimes mentioned that this is how the farm looks with the current management and that if someone else farmed here it would look different and that is fine, in fact that is great.

Farming is about the individual that drives the system. The plough was sold at Yatesbury in 2003 because a different system was envisaged without the use of a plough. While having it, it was tempting to just make a field look better (browner) by ploughing an already tilled field, which may not have needed to be ploughed. If a farmer loves ploughing, and believes that not ploughing will not work, then there is a potential to encourage the intervention to fail, so perhaps the change is futile. An untrimmed hedge will look untidy to some farmers and a wildlife haven to others, it takes more than a nudge to instil real adaptation.

Another example of reluctance to change is from a view of markets. It is sometimes mentioned that the organic market is a niche market and if others convert to organic methods the organic market would be oversupplied and collapse. The argument then develops to show that this is therefore a good reason not to adapt. That could be an argument for any emerging market. These examples demonstrate that at some point a leap of faith is required to engage in such a fundamental shift, a step change or trigger event as described by Sutherland et al. (2012). Perhaps a demonstration to a person that the leap or change has already been made in some way, by motivational interviewing as mentioned above (Miller and Rollnick 2004) could be a better approach. Optimisation of on-farm assets is such a trigger event, for example at Yatesbury alternative farming methods were reviewed initially to utilise unused permanent pasture, another farmer needed to upgrade and install a new grain store, moving to organic production removed the need for the new grain store and changed the investment requirements. This confirms what Sutherland et al. (2012) found, that change in farming practice often comes from trigger events, such as succession or large investments.

Cranfield et al. (2010) use survey data in Canada to show health and safety and environment concerns were the main reasons for adopting organic farming and this has not changed over time. A fellow PhD student said to a group of farmers, “pesticides will all be banned, maybe not tomorrow but in the future and the chemical companies that produce them are not developing new ones. Whether this is true or not the public don’t want pesticides.” Whilst this is a personal opinion it gains traction amongst farmers who are ever more in the public gaze. The discussion around glyphosate licencing (BBC 2017) in recent years has focused farmer attention to impending change and encouraged many farmers to start looking for alterative weed control methods, as demonstrated by the popularity of the Groundswell Event (FWI 2020)

2. A new vision

It might sound obvious to say that farmers are the key to the future of agriculture. However, agriculture has not been led by farmers for many generations; government support has lead farming, most recently in the UK with the EU’s Common Agricultural Policy. It is a farmer’s job to ensure the manageability and overview of the land and processes (diversity, integrity and sustainability). Their responsible organisation, design and optimization of the capacities is essential so that the complexity and size of the farm does not negatively affect the overall health (Vieweger 2018). Different farm scales require different processes and organisational structures to achieve a healthy system. A healthy farm must be sustainable and profitable by implication.

Farm optimization will be dependent therefore on the specific circumstances of the farm and the capabilities of the farmer. It is the farmer who is the key. Pfeiffer (1983) said "The human being who guides and directs the beginning, the course and the end of natural growth processes, is the strongest force in nature. His capacity is the final decisive factor." Of course, you might say, but most farmers underestimate the power and responsibility at their fingertips. Engaging farmers to farm as they see best could stimulate a wide range of farming systems. This diversity of farming approaches would not only stand up to the challenges of change but could also encourage biodiversity through diverse habitats (Senapathi et al. 2017, Hass et al. 2018). In order to reach this goal of a diverse farming outcome, in a sustainable farming context, Pretty (1994) says that learning needs to be participatory to be effective because it will need to embrace the values of all. This is very challenging given variability in the type of people who farm. Indeed, some would feel out of place in a city or at a university, so often the only place to engage with farmers is on a farm. Kilpatrick and Rosenblatt (1998) draw on data gathered from Australian farmers to suggest five reasons why farmers might prefer to learn by seeking information rather than attending training, 1) a preference for independence, 2) familiarity with a highly contextual learning mode, 3) lack of confidence in working in training settings, 4) a preference for information from known sources, and 5) a fear of being exposed to new knowledge and skills.

Farmers would benefit from engagement in participatory learning, rather than (government) support (Kilpatrick and Rosenblatt 1998). In analysing farmer education it is important to remember the tacit knowledge that farmers already have (Curry and Kirwan 2014) and ensure farmers value it. A farm rating system could further engage farmers, similar to the simple Food Standards Agency food hygiene rating system for catering establishments, along the lines of the Public Goods Tool (Gerrard et al. 2011). Despite the interest shown here in this aspect of engagement, this is another social science project that is well beyond the scope of this thesis, though this research has highlighted the need for it.

3. Adaptation

3.1 **Stability from vulnerability**

“Agricultural vulnerability to climate change is one of the greatest challenges facing the sustainability of the global food system.” (Mase et al. 2017). However, sitting here writing this thesis in the midst of the Covid-19 pandemic crisis, another great vulnerability in the food system has been realised. There will be many papers to come on this, notwithstanding the papers already highlighting the link between our current food system and viruses (Nelson et al. 2015, Dhingra et al. 2018). However, from a practical perspective, there are many variables that affect farming. Modern, industrial or chemical (conventional) farming seeks to stabilise (or maximize) production and income using artificial fertilisers, medicines and pesticides (Smith et al. 2007). These are used as, targeted short-term solutions (Watson et al. 2002), cures to problems relating to soil fertility, animal fertility, pests, disease and weeds. The conventional system uses these inputs to create a perceived stability. Perceived because the stability of simplified systems in modern agricultural landscapes is not self supporting - it relies on these outside inputs. These direct remedies often fail to address the systemic weakness that has caused the original symptom. They cause a systemic vacuum of communication between the biological organisms in the conventional system (see section 4, Homeostasis). A direct remedy cure may often cause unforeseen consequences despite short-term benefits. Some of the long-term consequences of this curative approach are a) the extensive use of fossil fuels and associated greenhouse gas emissions, b) pollution from leaching fertiliser and manures, agrochemicals or medicines and c) soil degradation; in particular through loss of carbon which impacts soil function and also contributes to carbon dioxide accumulation in the atmosphere (Power 2010). Notwithstanding that, the adoption of alternative farming approaches in temperate climate systems is typically associated with a general yield penalty (Mader et al. 2002, de Ponti et al. 2012, Seufert et al. 2012), though this can be compensated for by increases in crop quality (Lairon 2011). Although in climate extremes organic systems have been shown to out yield intensive input based systems (Lotter et al. 2003). In their experiment at the Rodale institute in the USA, Lotter et al. (2003) found that in four out of five drought years through 1984-1998, the organically managed plots yielded better than the conventional ones. Their organically managed soils retained more water and captured more than the conventionally managed plots and in “torrential rains” the organic soils captured approximately 100% more than in the conventionally manged soils. They propose that this improvement in water holding capacity accounted for the improved yields. In a 7-year experiment Smolik et al. (1995) showed less variability of net income for organic than conventional farms, interestingly they also found their reduced tillage conventional system was the least energy efficient system. Two more authors have shown that organically managed crop systems have lower long-term yield variability (higher stability), (Henning 1994, Peters 1994) as cited in (Lotter et al. 2003).

The thesis hypothesis in this context of stability is: retaining biomass increases crop yield, and exploring yield variation by year. This was postulated because the leaf litter from retaining crop residues provides labile carbon which is a good source of food for soil organisms to enable nutrient cycling (Birkhofer et al. 2011, Frouz 2018). There was no difference between the standard and enhanced treatments for yield or for year. Yield and year, however, were confounded by crop effect and there was insufficient data to explore variation of individual crop yield by year. The lack of variation by treatment can be explained by the fact that the standard treatment system is already a good system in this context. The difference between the two systems, that is the retention or removal of crop residues, must be small compared to the similarities of the systems: the two-year diverse ley (also see Chapter 4 Discussion). The two-year diverse ley provides a mixture of herbs, grasses and legumes that supply well known services which include, nitrogen fixation (Carlsson and Huss-Danell 2003), diverse legume-based mixture effect (Döring, John A. Baddeley et al. 2013), enhanced plant community rooting distribution especially at depth (Mueller et al. 2013), compensatory population dynamics (Morgan Ernest and Brown 2001), sampling and niche differential effect (Tilman 1999), rhizosphere deposition (Jones et al. 2004, Jones et al. 2009), root plasticity of communities (Campbell et al. 1991, Wijesinghe et al. 2001) and microbial activity and carbon storage (Lange et al. 2015).

These benefits can be summarised in the term **bio-cultivation**: bio meaning of life; cultivation in this context meaning: firstly growing, developing or promoting soil flora and fauna; and secondly in terms of soil tillage by the soil flora and fauna. Bio-cultivation is a term used here to describe this method of cultivating and tilling the soil that relies on the activity of growing plants and soil organisms, which will structure, aerate, mix and hydrate the soil with reduced need for mechanical intervention in agricultural situations. Bio-cultivations is an intrinsic outcome of ley farming systems especially with diverse mixtures of species.

Plant rhizodeposition is a dominant influence, it is an important source of sugars and also amino acids for soil organisms (Jaeger et al. 1999). Root exudates account for a large proportion of the carbon fixed by plants through photosynthesis (5-10% (Jones et al. 2004), 21% (Mendes et al. 2011), 20% (Hütsch et al. 2002)). Plant roots have been shown to be more important than above ground plant residues in soil carbon storage, the optimized coefficient for root-derived carbon was about 2.3 times higher than that for above-ground plant residues (Kätterer et al. 2011). This confirms the experimental finding that the quantity of above ground plant residues retained in the enhanced treatment, compared to the standard, was insufficient to result in a change in crop yield (Chapter 4) or in SOM (Chapter 2).

3.2 **Resilience**

At the beginning of the exploration of the literature, existing scientific evidence was explored to counter or support the established agroecological farming system in the experiment and to demonstrate its efficacy. This review is set out in the main thesis introduction. There is a good deal of literature about resilience in agricultural systems (Falkenmark and Rockström 2008, Cornelis 2014, Doring et al. 2015). Resilience in biological systems implies an ability to bounce back or return to the original form following a challenge, it is the ability to cope with a challenge (Gunderson 2000, Doring et al. 2015). Resilience focuses on recovery of a system after a shock (Doring et al. 2015). Historical farming (before chemical inputs) and modern organic farming sought and seeks to prevent variability and provide a resilience in crop production through the building up of soil fertility and use of crop rotation. This supplies nutrients to crops, which in turn provides balanced food to animals, prevents disease and reduces pest infestation (e.g. through harbouring/accommodating predators) (Watson et al. 2002). It promotes the idea that health is interconnected and perhaps infectious, “The health of soil, plant, animal and man is one and indivisible” (Balfour 1943), today it would be prudent to add: biodiversity and eventually, because of the global impact of agriculture, the health of the whole planet. For example, we are beginning to understand these links through the current climate crisis and also the food system vulnerability through the current COVID-19 pandemic (Nelson et al. 2015, Dhingra et al. 2018, Hass et al. 2018).

Financial comparisons of the two approaches show that conventional farming increases the cost of production as the inputs clearly need purchasing (Pimentel et al. 2005). As a counter to this, the farmer will expect an increased income from higher yield. However, farm business analyses have shown that the organic farming system can be more profitable (Scott 2018). The negative consequences of the conventional method through pollution or soil degradation are either externalised (the costs are not borne by the farm) in the case of pollution, or slow to evolve and become apparent in the case of soil degradation. With the alternative method, investment in soil, through green manures, composts and or leys, builds up a source of inputs that plants draw upon and interact with. This is often through symbiotic relationships with soil microbes such as mycorrhizal fungi or filamentous bacteria. The idea is that the more the soil community grows and creates a circulating economy of life the more this dynamic can be interacted with and drawn upon, to increase the positive and healthy functioning of plants. This was measured in this experiment, in terms of soil organic matter, labile carbon, soil aggregate stability with rapid wetting and meso fauna family counts. Another way of envisaging the alternative approach is as an insurance policy which is constantly paid into by investing in the soil, especially through biodiversity, this pooling then silently pays out when called upon, particularly in challenging conditions (Folke et al. 1996, Yachi and Loreau 1999). This thesis has explored the hypothesis of a living insurance policy provided through edaphic means (by living soil). Paying into the policy continually by feeding the soil life with plant biomass and root exudates then allows, when the conditions require, the soil to pay back in improved soil functioning: water storage to reduce flooding or drought; nutrient cycling and storage to reduce leaching of minerals and enabling feeding of cash crops.

One of the hypotheses from Chapter 4 states that enhanced biomass addition would increase crop quality or quantity in the experimental site farming system. No change in yield or quality through retaining above ground in situ grown plant biomass was found. Despite current understanding of Dunn (2006) and Schmidt (1997) as cited in (Heijden et al. 2008), which could have expected a decrease in yield after leaving plant residues in-situ. Not forgetting that the experiment was comparing two organic systems, rather than an organic and non-organic in the above. A comparison of the enhanced and standard systems was discussed in section 3.1 (and Chapter 4) leading to the conclusion that the benefits in both treatments from the two-year diverse ley below-ground rooting activity are much larger than the retained above-ground biomass in the enhanced treatment. Any retained biomass quality would vary over the rotation. During the ley phase low C:N residues might provide the thermodynamic factor (Bosatta and Ågren 1999, Lehmann and Kleber 2015) required to breakdown the high C:N straw residues from cereals, without detriment to crop yield expected above. This provides the first original contribution to knowledge in this thesis, no yield loss was found when retaining crop residues.

3.3 **Governing dynamics and collective action**

Farm management training has led to the common practice of focusing on enterprise gross margins as the ultimate guide in assessing the contribution of each farm enterprise to farm profitability. If at the farm level the farm enterprises are viewed as a collective rather than the individual level of the enterprise gross margins, in economic terms the whole farm profit, a better cooperative systems outcome can be visualised. This is explained by John Nash's equilibrium, also known as governing dynamics, which has been used to demonstrate the positive outcomes of cooperation (Lozano 2007), the section below on homeostasis develops this further in biological systems by looking at species cooperation. It demonstrates the principle where, if decisions are made on a collective approach rather than an individualistic approach, the outcomes will be greater than viewing each individual decision separately. Glimcher (2002) cites several applications of this game theory to biological questions, in a moose choosing grass or algae or a monkey choosing a mate. Take the example of cattle in a mixed farm, the simple equation of costs and income (enterprise gross margin) is far too simplistic to fully perceive the cattle contribution to the whole farm system. Cattle contribute to the soil organism community (Birkhofer et al. 2008); cattle spread the microorganisms that are developed in their gut around the farm and fields, they spread earthworm eggs, they encourage biodiversity through the food chain by feeding insects and birds, the cattle form a collective with the other farm organisms. Grazing of grassland by cattle increases sequestration of carbon in the soil, compared to un-grazed (Reeder and Schuman 2002). All these factors currently don't form part of the business accounts, yet they contribute to the whole farm output or to public goods beyond the farm.

In this vein, Chapter 2 addresses the critical hypothesis that adding biomass increases topsoil and subsoil soil organic matter. This study shows that the positive control treatment gave higher SOM increases at both 0-100 mm depth and 100-300 mm depth compared to the other treatments. The enhanced treatment was not different to the standard, however there appeared to be a trend of greater increases in SOM in the enhanced at both sampled depths. This demonstrates those non economically accounted for factors can be impactful. The enhanced treatment which retained crop residues and had a two-year diverse ley, was no competition for the positive reference treatment with five years diverse ley, in increasing SOM. As a direct consequence of this research the farm has already adapted the crop rotation to lengthen the diverse ley phase from 2 to 3 years.

A predicted maximum SOM was extrapolated in Chapter 2: 67.5 g.kg^{-1} SOM under the enhanced and standard experimental treatments. The maximum SOM under the positive reference was not seen as it was beyond the scope of the experiment. Any farming system will have a maximum SOM level as described by Machmuller et al. (2015) in their conversion of cropped land to pasture. This experiment clearly confirms the principle of carbon saturation discussed in Chapter 1 (Hassink 1997, Six et al. 2002), whilst remembering that in the Thesis Introduction it was explained that the absolute level of SOM is not important for soil health it is the direction of travel that is critical: to be gaining not degrading. This is because different soil types will have different SOM capacities, for example sandy soils are more difficult to store SOM than clay due to their soil particle size. However, with more and more focus on the ability of soils to sequester carbon (Lal et al. 2018, Smith et al. 2018, Bossio et al. 2020) the absolute levels of SOM are now seen as critical in climate change mitigation.

Discussions about methane emissions (Steinfeld et al. 2006) have highlighted the negative impacts of industrial cattle farming. Highlighting the process of turning fossil fuels into methane and beef or milk in some conventional farming models. As opposed to the alternative and traditional approach of the conversion of solar energy through photosynthesis to pasture cellulose (which humans cannot consume), which through their system of microbial digestion, cattle can convert into human food (Niggli 2009, Garnett et al. 2017, Lynch 2019, Davis and White 2020). Methane is a by-product of this system which has further implications, though methane has a half-life of 8-10 years meaning it doesn’t have the effect on global warming some suggest (Allen et al. 2018, Lynch 2019). Faeces are another by-product of enormous value when used correctly, or enormously polluting when not (Reeder and Schuman 2002, Chadwick et al. 2011, Machmuller et al. 2015).

Whilst conducting a carbon audit using the Farm Carbon Toolkit for the whole farm soil organic matter (SOM) was found to be increasing by approximately 2.2 g.kg^{-1} per annum. The audit has also identified that cattle are contributing 75% of the farm emissions. The total sequestration from SOM together with hedgerows, woodland and field margins means that sequestration is about ten times more than the greenhouse gas emissions. It is perhaps no surprise that the word organic used with farming comes from the term organic meaning of plant or animal life or substances plants and animals are made of (Northbourne 1940), these substances in chemistry refer to organic compounds and the study of carbon based (organic) compounds (with covalent bonding).

The enterprise gross margins approach on an annual basis can sometimes miss these subtle positive/negative interactions and feedbacks. As a scientist, farmer, or citizen, it is often good to stand back and take the broader view and challenge the common assumptions.

4. Homeostasis and adaptability of living systems

There is a fundamental stabilisation principle that governs natural systems that gives them a type of resistance or resilience to fluctuations. In biology this equilibrium is found in living organisms, but more than just coping with shock, living systems have an ability to adapt to new conditions or shocks with a constant rebalancing, this smart resilience is called homeostasis (Cooper 2008).

4.1 **The origins of homeostasis as a concept**

Homeostasis is an altogether different concept to resilience and was first described by Walter B. Cannon in 1925 (greatly influenced by Claude Bernard, a French researcher from the previous century (Cooper 2008). Cannon (1925) as cited in Cooper (2008) described six parts to homeostasis shown in Table 5.1.

Table 5.1 Six parts to homeostasis (Cooper 2008)

1. In an open system, such as our bodies represent, complex and subject to numberless disturbances, the very existence of a poised or steady state is in itself evidence that agencies are at hand keeping the balance, or ready to act in such a way as to keep the balance.
2. If the state remains steady, there is an automatic arrangement whereby any tendency toward change is effectively met by increased action of the factor or factors which resist the change.
3. Any factor which operates to maintain a steady state by action in one direction does not act at the same point in the opposite direction.
4. Factors which may be antagonistic in one region, where they effect a balance, may be cooperative in another region.
5. The system of checks which determines a balanced state may not be constituted of only two antagonistic factors; on either side there may be two or more, brought into action at the same time or successively.
6. When a physiologic factor is known which can shift a steady state in one direction, it is reasonable to look for a physiologic factor or factors having a contrary or counter-balancing effect.

Homeostasis is the act of an organism adapting to change. It is important to note that this adaptation, does not necessarily involve a return to the former equilibrium. We can take the development of an athlete as an example. Cooper (2008) also explains for Bernard, who influenced Cannon, there must be an overall conductor (or orchestrator): ‘‘in the perfected animal, whose existence is independent, the nervous system is called upon to regulate the harmony which exists between all these conditions’’. Here we have two key notions in Bernard’s thinking: ‘‘regulation’’ and ‘‘harmonious whole.’’ Instinctive responses represent the basis of the regulatory behaviours animals use to maintain homeostasis, rather than learnt responses such as Pavlov’s dog (Woods and Ramsay 2007). If homeostasis means life, then perhaps optimum homeostasis is health.

4.2 **Organisms to ecosystem, species interaction in community balance**

Biological organisms rely on and are continually rebalancing with the varying of inputs (food, sunlight, water, air) but particularly energy (Morgan Ernest and Brown 2001). When Morgan Ernest and Brown (2001) looked at species balance in ecosystems they found the species composition (individual species population) varied more than species richness (range or number of species), indicating the community competition is less than intra species competition. This can be because different species often use different resources and so compete less than intra species organisms. Tilman (1999) explains this result as both from the greater probability that a more productive species would be present if there is higher species diversity/richness (the sampling effect) and from the better ‘‘coverage’’ of habitat heterogeneity caused by the broader range of species traits in a more diverse community (the niche differentiation effect, each species can operate in a different niche avoiding competition).

The question is, does the community act like an organism or are the individual components competing? Can it be inferred from Morgan Ernest and Brown (2001) and Van Bruggen and Semenov (2000) that a living soil operates as a homeostasis system, as they use this term? If so, what are the lines of communication between species, is it more than predator-prey? Is the search for energy an instinctive one or a learnt one? In order to take the homeostasis system to a higher level can we describe forest or farm homeostasis as an ecosystem homeostasis? Above in the text, conventional farming inputs were accused of creating a systemic vacuum in communication between the biological organisms operating in the conventional farming system. What was meant by that is the chemical fertilisers and agrochemical pesticides perhaps disable the communication pathways that occur in natural functioning homeostasis (eco)systems, either because they are redundant or the introduced chemicals block the natural chemical signalling pathways by killing the participants (fungi/bacteria) (Puglisi 2012, Gunstone et al. 2021). Some of these inter-species signalling pathways are only just been discovered, they are likely to have resulted from millions of years of co-evolution, research is only starting to unravel the mechanisms for such interactions which is often based on sophisticated chemical communication (Lavelle et al. 2006). Another explanation may be co-signalling from the environment, for example, climate, habitat formation or energy supply (Scheu et al. 2005), where the same external signal is received by all the species in the community but they each respond differently and instinctively. Tilman (1999) supports that edaphic and climatic are more important ecosystem triggers than diversity of species, perhaps because they send better negative feedback signals than other species? Lavelle et al. (2006) suggest fundamental evidence for self-organisation of soils in Table 5.2.

Table 5.2 Evidence for self-organisation in soils (Lavelle, Decaëns et al. 2006)

Evidence for self-organisation of soils	example
1. They are characterized by order where disorder would otherwise have been predicted	Soil horizons, pore size distribution, community structure (order)
2. Structures and processes mutually reinforce one another	Maintenance of structural soil porosity by invertebrates and roots that enhances their own activities, with positive feedback effects on the maintenance of suitable conditions of porosity to sustain biological activities
3. The system maintains order within boundaries through internal interactions	Functional domains of soil ecosystem engineers have recognizable limits that can be defined, (macro-aggregates and populations of earthworms, termites and roots often occur in patches within which soils have notably specific characteristics and functions)
4. Far from equilibrium, these systems are in a metastable equilibrium	When eliminated by aggressive land management practices, the environmental conditions that they maintained in their sphere of influence may change drastically; one example may be the disappearance of control exerted by plant parasitic nematode communities on their most aggressive species when nematicides are applied ultimately leaving the most aggressive species with no competitors

Referring to the hypothesis explored in Chapter 3 that in-situ grown biomass input increases soil meso fauna, the soil meso fauna community has grown with biomass addition and retention of crop residues, finding new homeostasis balances. Total meso fauna had a higher count in the positive reference and enhanced plots compared to the standard and negative. Indeed, the enhanced gave higher counts of mesofauna than the standard treatment. Positive and enhanced gave higher counts than the negative in all cases. This indicates that meso fauna are influenced by the quantity of biomass added and that different meso fauna families find different balances in different biomass systems. But also, biomass was not the only controlling influence as enhanced treatment produced most Acari demonstrating an interaction with, perhaps tillage. All the meso fauna families (collembola and acari) were present in all the treatments, confirming the findings of Morgan Ernest and Brown (2001) above, that species composition varies more than species richness.

4.3 **Farm homeostasis**

Homeostasis can also be applied to larger and more complex living systems that can be thought of as an organism, such as an ant colony where a single ant cannot survive alone (Oldroyd and Fewell 2007). A cow is a living organism, yet it functions as a system which relies on cellulose digesting bacteria living as part of the cow’s digestive system. In both these cases there are communication/orchestration and a harmonious whole, which are the two requirements for homeostasis (Cooper 2008). Berkes et al. (2012) show how the idea of a self-renewal capacity of socio-ecological systems is not a new one. In the USA, Leopold in the 1940s wrote about land health, before the term ecosystem was used (Berkes et al. 2012). In farming circles in England, Lord Northbourne in his book, Look to the Land, wrote about the farm as an organism (Northbourne 1940). Northbourne’s ideas of ‘the farm as organism’ can be traced back to Pfeiffer (1938) as cited in (Paull 2014). In Germany in 1924, Rudolf Steiner’s Agriculture Course had inspired Pfeiffer where Steiner said “Truly, the farm is an organism” (Paull 2014). Whilst looking at the current texts where homeostasis is used when discussing ecosystems, although harmony is often implied, the communication element to homeostasis within ecosystems is not developed (Morgan Ernest and Brown 2001, Woods and Ramsay 2007, Dyke and Weaver 2013, Doring et al. 2015). Although homeostasis is said to be an instinctive response mechanism (Woods and Ramsay 2007).

In nature and natural ecosystems, the feedback loops originally proposed as homeostasis of an organism, can be said to exist through natural mechanisms such as plant, fungi and bacterial symbioses and also plant and insect interactions (signalling) as discussed. At the farm system level, the orchestrator will be the farmer providing the higher intelligence, leading the connection of negative feedbacks (Cooper 2008) which form the communication to the control systems, to allow the compensatory mechanisms to function (Morgan Ernest and Brown 2001) but also and importantly, the anticipatory preparatory responses (Woods and Ramsay 2007). In farming methods based on less or no chemical inputs (alternative farm systems), the interconnectedness of the soil, plants and animals, allows increased communication between organisms facilitating natural feedback loops or anticipatory responses, and this creates a greater propensity for self-regulation which can be called farm orchestration and must evolve from the soil.

This study found several variations in response variables as a result of differing biomass inputs associated with the different treatments. The meso fauna dynamics which were found in Chapter 3 and discussed above, demonstrate the interconnectedness of the soil community and the impact different systems can have on the community balance. This together with the finding from Chapter 2 on SOM change over the 5 years of the experiment indicate the self-regulating ability of the soil community particularly at different biomass inputs. Chapter 4 demonstrates that the enhanced treatment does not have a negative impact on yield or quality compared to the standard, as some might have expected. Another outcome from Chapter 3 was the increase in soil aggregate stability under the positive reference. These can be viewed as farm homeostasis at work, beneficial farm outcomes from feeding the soil. The increase in mesofauna counts from retaining above-ground biomass makes the second original contribution to knowledge in this thesis.

4.4 **Variability**

Output from these living systems will inevitably vary from year to year even if they function with homeostasis and therefore homeostasis is a better concept than resilience when looking at living systems. It is not just about the ability to withstand shock and recover, adaptability is fundamental. Indeed, if the energy input to the system varies (solar radiation incidence for example) the output must vary as plants function with photosynthesis. However, the rainfall in any given growing season will also vary but improved soil function can spread out the peaks and troughs caused by changing rainfall and sunshine, smoothing out the water resource available through the water holding ability, for example by improving SOM and soil pore space, in an effective functioning soil (Falkenmark and Rockström 2008).

Chapter 2 tested the hypothesis that adding biomass improves soil water holding capacity. Water infiltration results showed no effect of treatment. A lower bulk density implies increased water holding capacity and bulk density results in Chapter 2 varied greatly with depth. At 0-100 mm the enhanced and the standard both gave lower (better) readings to the negative (not the positive). At the 100-300 mm and 300-500 mm depths the positive gave lower readings than all the other treatments (except standard at 100-300mm). Rooting depth and time to develop roots and structure in the positive may account for the improvement at depth. At the surface previous tillage is the likely cause of lower bulk density results together with soil biota activity and retained crop residues. All these positive biota effects have been termed bio-cultivations here, referring to the activity of roots and soil organisms creating structure and aerating the soil through their gluing of soil particles and burrowing effect.

Research in the desertification-prone savannas of Sub-Saharan Africa has found that “drylands are in fact not that dry after all” (Falkenmark and Rockström 2008). Meteorological rainfall in these savannas showed no recent change, low crop yields may therefore be due to the soil’s critical inability to supply moisture in dry spells, following soil degradation due to poor management (Falkenmark and Rockström 2008). Adaptation in land management practices can quickly reverse this situation, particularly through “more biomass per drop” of rain (Stroosnijder 2009). The soil plays a critical role in mitigating agricultural drought conditions through the effective soil function of water holding capacity. Degraded soils further exacerbate drought conditions by contributing to hydrological drought caused by rain runoff from compacted soils and from the reduced evapotranspiration due to reduced plant growth (Cornelis 2014). Soil function is therefore key to reducing variability in crop growth.

Chapter 3 looked at the hypothesis relevant to this, adding biomass improves soil aggregate stability following rapid wetting. Soil aggregation being an indicator of soil structure. The results showed that the positive control stood out with statistically better aggregate scores. The planting of a permanent crop is the single most effective way to improve soil properties through removing tillage, allowing perennial roots to establish and soil communities to flourish (Montgomery 2007, Smith 2008, Machmuller et al. 2015). The treatments with tillage (enhanced, standard and negative reference), all showed reduced aggregate stability irrespective of biomass additions. Bulk density also indicates soil structure and water holding capacity and below tillage depth the positive reference gave lower bulk density results. This would imply greater water storing capacity, drought tolerance and flood resistance.

One last, interesting question is posed by Odum (2014), if ecosystems enjoy homeostasis do they age as organisms do, eventually losing their homeostasis? Most certainly yes for farms, these are visible through the cycle of the manager/farmer/orchestrator and are reborn with succession as indicated by Sutherland et al. (2012). The answer is probably yes more generally, though the time scale would vary with the scale of the organism, for an ant it is a season, for a planet, well, slightly longer. For biological organisms, life involves a rebirth, for ecosystems the death of one ecosystem precipitates the birth of the next generation, asexually.

5. Cropping systems recommendations

This research into high biomass rotation has explored soil regeneration, weed burden and crop productivity and produced some globally important results. The international goal of 4 per 1000 (0.4%) increase in soil organic matter (soil carbon) per annum (Minasny et al. 2017), has been exceeded in this study. All the biomass addition treatments increased SOM to 100 mm, standard treatment by 1.21% yr^{-1}, the enhanced treatment by 1.59% yr^{-1} (no statistically significant difference between standard and enhanced) and the positive reference by 3.14% yr^{-1}. The positive reference also increased SOM at the 100 mm to 300 mm depth by 1.57% yr^{-1}. The 4 per 1000 initiative aims to demonstrate “that agriculture, and in particular agricultural soils can play a crucial role where food security and climate change are concerned” (4p1000 2015). This is focused on a compensation for the global emissions of greenhouse gases by anthropogenic sources (Minasny et al. 2017). As chapter 2 discusses, adding SOM has the twin benefits of both capturing carbon to mitigate for climate change and regenerating soil function to increase adaptive capacity to climate change.

5.1 **Importance of having diverse perennial crops**

Perennial crops with constant soil cover are recognised as providing better conditions for soil improvement than annual crops (Poulton et al. 2003, Machmuller et al. 2015). This thesis research used a five-year diverse ley in the positive refence treatment with the aim of achieving rapid and maximum soil regeneration. As shown in Chapter 2, a 3.14% yr^{-1} increase in SOM resulted to 100 mm depth and 1.57% yr^{-1} increase from 100-300 mm depth. However, there is great demand for annual crops such as vegetables and cereals (Tilman et al. 2011), especially as crops can generally feed more people than livestock in terms of calories and protein (Spedding 1979, Schiere et al. 2002). A short-term ley as part of a crop rotation, as demonstrated in this experiment and by others (Powlson et al. 2011, Poulton et al. 2018), can provide a degree of these diverse perennial crop benefits whilst still facilitating the demand for annual crops . The degree of benefit will vary depending upon the number of years the ley is retained with the longer the ley phase the greater the increase in organic matter (Johnston et al. 2009), previous experiments have focused on a 3-year or greater ley phase (Poulton et al. 2018). Globally important carbon sequestration, as provided by a 5-year diverse ley and a 2-year diverse ley being part of a 7-year crop rotation, is a third original contribution to knowledge in this thesis.

Chapters 2 and 3 show improvements in soil and biota characteristics with a 2-year diverse ley and further improvements when moving from a 2-year ley (standard and enhanced treatments) to a 5-

year ley (positive reference). In this experiment the enhanced and standard treatments included two years of the diverse ley. Traditional mixed farming in the UK, which gained ground in the 1930s due to improved cultivars of grasses and clovers, used such systems of short-term leys (Johnston et al. 2009). They only became less popular with the increased use of agrochemicals and synthetic fertilisers, and with the continuous need for capital investment, which had encouraged farm specialisation (Watson et al. 2005). The diverse ley also provides other services such as range of nectar sources for different pollinators (Storkey et al. 2015), suppresses weeds and increases herbage yield (Döring et al. 2013, Sturludóttir et al. 2014) with no consequential decrease in nutritive value (Sturludóttir et al. 2014), as well as enhancing soil function through the numerous bio-cultivation effects already described above. These bio-cultivation effects till the soil at a micro and macro scale and cultivate soil biota which structure, aerate and mix the soil with reduced need for mechanical intervention in agricultural situations.

5.2 **Impacts of crop residue removal**

Retaining crop residues increases mesofauna counts. Mesofauna such as Collembola and Acari provide various soil functions including nutrient cycling, pathogenic fungi control and nutrient provision for plants through high N faecal pellets (Neher and Barbercheck 1998, Frouz 2018). Despite them being less well known, mesofauna are a group of soil organisms with wide functional diversity (Wagg et al. 2014).

Retaining crop residues had no effect on weed burden, crop yield nor quality. Whist weeds can impact crop performance, weeds can be virtuous providing important ecosystem services such as, flowers for pollinators, protection for insects, food for farmland birds and roots to grow soil organisms (Marshall et al. 2003). Other research has found that small, diverse and non-competitive weeds can make an important contribution to farm biodiversity whilst having no impact on crop yield (Adeux et al. 2019).

Residue quality also needs to be considered when retaining residues. Chapter 4 discussed the implications of residue quality variation. The enhanced treatment contained two distinct residue types, crop straw residues from the cereals, and mixed residues from the 2-year diverse ley (also present in the positive reference for 5 years). Looking at these two separately: Firstly there is an expectation that straw residues may lead to a lowering of crop yield due to limited nitrogen availability in the system (Dunn et al. 2006, Heijden et al. 2008, Smith and Read 2010), though the experimental results (Ch 4) gave no change in yield. Powlson et al. (2011) notes that in systems using nitrogen fertiliser, removal or addition of straw is likely to have little effect on SOM but that it is unwise to remove straw every year due to a reduction in soil physical properties that may result.

Secondly as Chapter 4 discusses, the mixed residues of the diverse ley are likely to have an overall low C:N ratio (Bending and Turner 2009), a mix of crop residue types is more likely to benefit a diverse community of soil organisms (Kramer et al. 2012) and in turn enhance soil C and N (McDaniel et al. 2014).

Over the five years of the experiment retaining or removing above-ground crop residues from the rotation had no effect on SOM nor yield, despite the gain in mesofauna biodiversity already mentioned. Given the positive effect of the diverse ley in both the enhanced and standard treatments, compared to no diverse ley in the negative reference, it might be concluded that the diverse (below-ground) root effect is greater than any retention of above-ground biomass. Jackson et al. (2017) confirm this in their review of biomass addition experiments, where root input had on average 8.1 times the effect of the same mass of above-ground litter in stabilising SOM.

5.3 **Testing the system**

Any economic review of the outcomes of system change will be best made with a whole farm approach, considering financial and non-financial rewards. Testing soil health is a complex exercise with no one simple test available. Soil health is commonly defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (Lehmann et al. 2020). Improvements in soil health can be measured by observing the changing soil functions through the active perception of an experienced land manager, as many farmers already understand what good soil function is (Curry and Kirwan 2014). Tools such as the tests available in Table 1.2 can aid these observations.

An ever increasing array, or ladder, of soil organic carbon/SOM tests are becoming available following the climate change mitigation imperitive to sequester more soil carbon (4p1000 2015). Though carbon is a fundemental part of soil organic matter, historically understood to make up 58% of SOM (Pribyl 2010), the science, in particular the ecology of organic matter is still emerging and not well understood (Pribyl 2010, Bardgett and van der Putten 2014, Jackson et al. 2017). The carbon content of SOM has a theoretical range of 40% of SOM in young soils, to 72% of SOM in older acid peat soils (Pribyl 2010).The interactions of carbon molecules within the SOM are complex, dynamic and depend on the interplay of many species (Pribyl 2010, Wagg et al. 2014). Therefore, these tests need care with their use and interpretation (Roper et al. 2019).

Loss on ignition is a cost effective test to follow the development of SOM over time, a first rung on the ladder. Extreme caution must be taken in understanding the methodology and why results may vary. These include the effect of sampling depth, sample location, time of year of sampling, soil texture (clay content), soil profile ($CaCO_3$ distribution) as well as laboratory method, such as combustion temperature (see Chapter 3), (Pribyl 2010, Hoogsteen et al. 2015). Soil testing at the outside the experiment in-field, on-farm is done in textural zones and using GPS tags. Using a repeated method to give a change over time in SOM can also eliminate some errors that might occur in both tests, such as $CaCO_3$ or water tightly bound in clay which are evident in loss on ignition testing. Carrying out the tests of the repeated samples at the same time (by storing the initial soil samples at $-20^{O}C$ until the second one is taken) and therefore at the same laboratory can eliminate unknown laboratory variations. Robust use of the scientific method will avoid misunderstandings, confusion and misleading results, giving confidence to farmers, advisers, policy makers and consumers where necessary.

Timing, repetition in space and time, knowledge of the soil zones and profiles, and understanding of the scientific method need careful attention to ensure results are valid. This attention to methodology is important when considering the impending context of carbon emissions trading (Baker et al. 2007, Neufeldt et al. 2013). To thoroughly test a proposed adaptation to a cropping system the scientific method is necessary to ensure the tests employed are not indicated just by chance and that the outcomes are replicable. The Appendix sets out some principles and questions for on-farm trials.

5.4 **Overall systems design**

The literature review and the experimental research have explored the benefits of retaining crop residues which have been viewed as part of the solution to soil degradation. Whilst there are benefits to retaining above-ground crop residues (section 5.2); there seem to be greater benefits accruing from below-ground activities of the diverse ley, confirmed by (Jackson et al. 2017). To encourage adoption, or readoption of mixed ley and cropping systems which incorporate these semi-permanent pastures, it will require exploration of income streams that support a reduction in annual cropping in favour of leys. These may include grazing of ruminant or monogastric livestock, including novel methods of feeding forage to monogastrics (Fog et al. 2017, Santamaria-Fernandez et al. 2017), subsidies for or trading of carbon sequestration, or biomass, biofuel and fibre production. Recent interest in cover crops in arable systems in the UK as a tool for soil improvement has sparked demand for a return of grazing animals to arable land. The shifting baseline syndrome (Pauly 1995) (see Chapter 1 section 5.3), describes where new observer set their baseline at the level which they don’t realise is already degraded by previous generations, therefore not seeing the total degradation that has accrued. This shifting baseline has been brought to light through the biodiversity and climate crises and can be overcome by the enlightenment of the current generation. Old and new solutions to soil regeneration will be found. Solutions to soil degradation for cropping systems from this research are summarised in Figure 5.1.

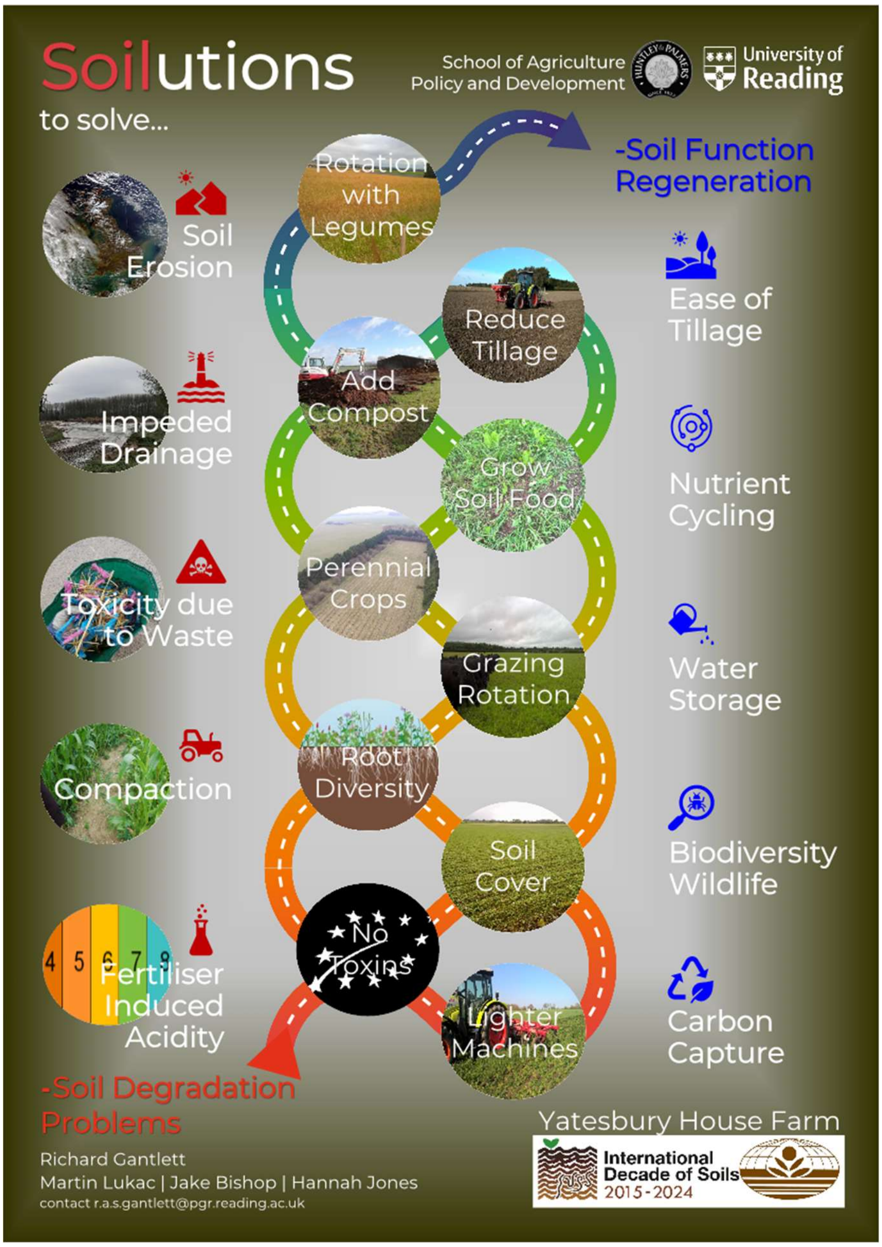

Figure 5.1 Soil-utions, to solve soil degradation problems in cropping systems. Problems, 10 cropping systems solutions and regeneration outcomes (poster for IUSS).

Limitations of methodologies

The main limitation of this research has been the duration of the experiment. SOM takes time to develop, five years is a short time over which to measure changes in SOM. Although changes were seen, if the experiment had been longer more differences between the enhanced treatment and the standard treatment may have become statistically significant. With this in mind the plots have been continued in one field where it is hoped that the progress of the crop rotation will be followed. Observations of the plots showed tillage to be less effective, with regard to weeding and mixing the soil, in the plots than in the surrounding fields. This was due to the inability to cross till effectively because of the width or length of the cultivator, which had a surprisingly noticeable impact on tillage effectiveness compared to soil surrounding the plots. For various reasons some of the observations were only carried out once or twice during the 5-year experiment. It would have produced more interesting results if the Brix test, leaf senescence and soil tests were carried out every year and several times a season to see the trends in development and give more opportunity for interactions to be observed. Resources will always be limiting in any application of the scientific method, though further investigation of SOM, measurement of soil carbon and observations of the numbers and species of soil organisms would have filled some gaps in the story from the experiment. In particular, the development of SOM and the roles that different soil organisms (other than mesofauna) play in soil regeneration. The effectiveness of different species of the diverse ley were not evaluated. The diverse ley seed mixture contains 33 varieties of 23 species and the effectiveness of each variety and species is unknown. Observations of the content of the ley for species diversity and composition could have drawn interesting data, such as variability in establishment or preferred conditions for each seed mixture constituent. However, using a large diverse mixture aims to provide both the sampling effect and the niche differential effect so that all the ideal possibilities of the community are included.

Future work

Dissemination of the results of this experiment is planned for the coming years together with a part continuation of the experimental work on farm to monitor the development of SOM and soil life as the rotation continues with adaptations. Events are planned to demonstrate the scientific method employed in this study and to explain the results. Thereby engaging farmers, advisors, environmentalists, local interested people, scientists and those in and working for government, in alternative methods of food production with multiple outcomes.

Fine tuning of the species mixture in the diverse ley could be achieved by studying the effectiveness of soil function improvement for varying mixtures leading to enhanced outcomes. Examining the roles that different soil organisms play in soil regeneration will improve knowledge of the regeneration process. Exploring the individual function of the mesofauna family members, in terms of soil structure forming processes, would add to the knowledge of aggregate forming processes and could influence soil biomass addition. Future work remains to be carried out investigating, in greater detail, the SOM analysis undertaken in 2018 in this study. Where higher furnace temperatures were used compared to the 2014 and 2019 SOM analyses (as discussed in Chapter 3). This could provide more certainty to land managers wishing to monitor their soils for carbon and give them confidence in the methods used.

Monetising the gains from soil function regeneration would be a good motivator for farmer adaptation and provides a future challenge for researchers. Many of these gains are to society generally, through ecosystem services, which makes the challenge all the greater and of higher imperative given the threats of flooding, biodiversity decline, food security and climate change. A calculation of the value of the public goods and ecosystem services flowing and accruing from these research outcomes would be timely. They would make a valuable outcome to soil regeneration achieved here and would aid the UK government in assessing payments to farmers that are proposed in the Agriculture Act 2020.

Developing a farm rating system alluded to in - the new vision - above, would be a positive start to engage farmers in adaptation. Further development of the concept of farm self-regulation (homeostasis) could have far reaching benefits both to farmers and through public goods provision. Optimum farm homeostasis, through the well-fed soil community, may both reduce the work for the farmer and provide multiple benefits in healthy systems in and beyond the farm. Viewing the farm as a whole living organism goes hand in hand with the new vision, it also sits comfortably within the ecological approach to science.

Concluding remarks

Change is coming for agriculture; the vulnerability of the modern agricultural systems becomes increasingly apparent with every passing year (Mase et al. 2017). The technological abilities to adapt our environment are growing ever stronger. Whether it is planting trees or felling trees, burning oil or capturing carbon, eroding soil or growing soil, loosing biodiversity or nurturing biodiversity. As human beings, our power to rapidly enact these alternatives grows each day at an alarming rate and the speed of enactment increases. Careful thought is needed about unintended consequences of our well-intended actions for they have enormous impacts. For example, adding compost to the soil can be good, but what if the compost is from urban waste that includes microplastics? The consequences of our actions need to be carefully understood. The scientific method gives farmers a tool to explore possibilities and explore adaptation. Here its direct application has been shown via scientifically valid on-farm research, which has been (relatively) easy and certainly worthwhile, in a farm system situation, giving three original contributions to knowledge (no yield loss from retaining crop residues, mesofauna counts increase with retaining crop residues and globally important carbon sequestration is achieved from a 5-year and a 2-year diverse ley in a 7-year crop rotation).

The beauty of the approach to farm adaptation where all farmers are treated as individuals - a new vision - is that there would be a whole range of diverse farm system outcomes, each farm different from the next, creating a range of outcomes which would make agriculture and our food system as a whole, more versatile and adaptable to change in the future and less vulnerable to shocks when they come. This would increase the adaptive capacity of agriculture. “We have come a long way since the early sceptics of organic farming” (Reganold and Wachter 2016), but if organic farming is to become mainstream there needs to be further engagement with farmers in adapting to change. Government needs to regulate against soil degrading practices described in the Introduction, at the same time as promoting a new vision of farms which encompasses the contribution of farmers to social and rural stability, food and fibre production, biodiversity and historic landscape maintenance, all of which evolves from a healthy living soil in farm homeostasis. Engagement with farmers needs to be at a level that suits the individual, gradual adaptation may suit some. On-farm demonstration has a good track record and motivational change by positive affirmation, which has been demonstrated in medicine, can bring lasting adaptation.

The General Introduction mentions that Yatesbury House Farm is working to produce soil akin to chernozem. Chernozem, black soil, is famous for supporting Europe’s breadbasket of Ukraine and central Russia, but also part of Midwest USA and Canada. Yatesbury Farm’s Blewbury and Yatesbury series soils (Findlay and Colborne 1984) (silty and clay loam over lower grey chalks) have shown their capacity to accumulate soil organic matter from diverse pasture, just as chernozem soil was built from diverse ancient prairie pasture. The soils across the farm are now in the same SOM range as Nosko (2013) found virgin fallow in Ukraine: typical loamy clayey chernozem, at 50 g.kg^{-1} SOM 0-300 mm, with a range of 31 to 45 g.kg^{-1} SOM for the cropped treatments. Yatesbury treatment plots compare favourably to this chernozem sample (see Ch.2. SOM in 2019 0-100 mm: enhanced treatment: mean=51.3 g.kg^{-1} (CI 37.5 to 65.1); standard treatment: mean=51.0 g.kg^{-1} (CI 37.2 to

64.8), at 100-300 mm depth: enhanced treatment mean=40.1 g.kg^{-1} (CI 28.6 to 51.6); standard treatment: mean=38.5 g.kg^{-1} (CI 27.0 to 50.0)).

This thesis reviews the value of soil in agriculture. It investigates the outcomes of a sustainable approach to soil regeneration primarily using diverse leys and that of growing in-situ biomass and feeding it to the soil. Chapter 2 highlighted that both enhanced and standard treatments increased SOM at 0-100 mm depth above global targets and the five-year diverse ley increased SOM many times more than global targets at both 0-100 mm and 100-300 mm depths. Chapter 3 indicates that mesofauna are influenced by the quantity of biomass added and that different meso fauna families find different balances in different biomass systems; crop residue retention did not affect weed burden; and 5-years of diverse ley improved soil aggregation. Chapter 4 concluded there was no yield or quality benefit from the enhanced crop residue retaining treatment, but importantly no yield decline either. Chapter 5 discusses the concept of stability, resilience and farm homeostasis in the context of inevitable change, it develops the self-regulating and adaptive concept of farm homeostasis in light of the outcomes of this doctoral research. Cropping systems recommendations are summarised with the soil-utions poster in Figure 5.1. Together these findings make the unique contributions to knowledge in this thesis.

The experimental influence at Yatesbury has been broad and deep: Broad, because the farm rotation has changed to adopt the positive outcomes of the positive control treatment by extending the diverse ley phase of the far rotation from 2 years to 3 years; deep, because the farm is now steeped in the scientific method and adaptations can grow with this approach.

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Appendix. How to set up on-farm crop trials

Some farmers will be keen to carry out farm trials with scientific rigour. This section aims to empower farmers to easily carry out these trials. Questions to ask and get answered before starting.

Timely and ongoing

a. What burning question needs answering without converting my whole farm?
b. What is the question I want to answer?
c. Who is asking the question and who is motivated to complete the work, what is the motivation?

Robust experimentation

d. Why Scientifically valid experiment is better than try and leave? What makes the experiment scientifically valid?
e. What system do I have in place to work around?
f. How is my situation different to other farms?
g. Replication
h. Control plots, Controls in experiments aim to eliminate the variables that are not being studied so this experiment can be compared with other experiments or situations and the results become more widely applicable. An experiment without a control is unique to the situation of the test and cannot be applied elsewhere.
i. Randomisation and repetition aim to eliminate the variation in location that might occur and the shear chance that one result occurs rather than another.
j. Randomised replicated plot design with controls, making it scientifically significant

Practicalities

k. It’s easy. It is effectively Controlled traffic experiments.
l. What machinery do I have that will form the plot sizes, how to make it practical with farm machinery?

m. What measurements can I take with that equipment?

n. What sizes are these machines?

o. What plot width and length works with my machinery?

p. Who will fund the work?

q. Who will manage the experiment?

r. Who will advise on setup?

Results (that can be widely used)

s. How am I going to take the measurements?

t. Which variables do I try to exclude?

u. What is the field history?

v. Choose a field, location where there is least field variation

w. What assumptions have I made?

x. What do I have to be concerned about, variation, what am I comparing with?

y. Natural variation, weather variation, field variation, outside influences

z. How am I going to analyse the results, who can help?

The Process (Chaney 2017)

Following these 10 steps will help you develop a successful on-farm research project.

1. Identify your research question and objective.
2. Develop a research hypothesis.
3. Decide what you will measure and what data you will collect.
4. Develop an experimental design.
5. Choose the location and map out your field plots.
6. Implement the project.
7. Make observations and keep records throughout the season.
8. Collect research data.
9. Analyze the data.
10. Interpret the data and draw conclusion