Chapter 12

Can soil improving cropping systems reduce the loss of soil biodiversity within agricultural soils?

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Summary

Soil biodiversity, including abundance and function of species living in the soils are important aspects of soil health, and acknowledges that soil is a living ecosystem. The decline of soil biodiversity can lead to a simplification of the soil food web and the inter-relationships as a result of poor soil management. The impact of agricultural management has been shown to reduce diversity, with damaging consequences for nutrient cycling, soil structure and potentially crop yields. However, research is often siloed and the effect of soil biodiversity on crop yields is overlooked by soil ecologists focusing on other ecosystem services; and the role of soil biodiversity on maintaining soil quality and improving crop yields is missed by agronomy researchers. Introducing specific soil improving cropping systems (SICS) have previously been considered as a method to combat soil threats (such as soil erosion or compaction) but have been overlooked as a method of reducing soil biodiversity losses within agriculture. As soil biodiversity loss is interlinked with these other soil threats, SICS will also potentially reduce the impact of them. Here, we review the range of SICS that can be utilised to reduce the threat of soil biodiversity loss, evaluating the effect of SICS on biodiversity across a wide range of organismal groups and consider the impact this will have on the sustainability of agricultural management. There are examples of measures and practices that combine high crop yields with the promotion of soil biodiversity. Selecting specific cropping systems designed to maintain or increase soil biodiversity (e.g., cover crops), promoting the stabilisation of the soil environment (minimum tillage), reducing chemical amendments (targeted spraying and biocontrol), or increasing biological amendments (adding organic matter) are all potential SICS that can be utilised.

Introduction

Soil quality and the protection of its functions are not specifically mentioned as a sustainable development goal (SDG) by the United Nations, but soil-related ecosystem services are implicitly linked to several SDGs, especially *No poverty* (SDG 1), *Zero hunger* (SDG 2), *Good health and well-being* (SDG 3), *Clean water and sanitation* (SDG 6), *Climate action* (SDG 13), and *Life on land* (SDG 15) (Bach et al. 2020). The European Commission defined the soil as having seven basic functions: *1)* Biomass production (including agriculture and forestry); *2)* Storing, filtering, and transforming nutrients, substances and water; *3)* Biodiversity pool (habitats, species and genes); *4)* Physical and cultural environment for humans and human activities; *5)* Source of raw material; *6)* Carbon pool; *7)* Archive of geological and archaeological heritage; (European Commission, 2006). Agricultural production is only one of these seven soil functions, the biodiversity as a pool is one of the others; it is up to agricultural management and the use of soil improving cropping systems (SICS) to prevent the loss of one function due to another. Research has shown that agricultural intensification across Europe has reduced soil biodiversity (Tsiafouli et al. 2015), however within extensive agricultural systems soil biodiversity can reach similar levels as permanent grasslands (van Eekeren et al. 2008).

Intensive agricultural systems have also been shown to impact the ecosystem services delivered by soil biodiversity, for example De Vries et al. (2013) showed that carbon and nitrogen cycling were directly linked to the soil food web across land use systems. It is commonly acknowledged that conserving soil biodiversity is key to improving and sustaining soil quality (e.g. Firbank et al. 2008, Handa et al. 2014, Crotty et al. 2015). Soil quality refers to "the continued capacity of soil to function as a vital living system, within ecosystems and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health" (Doran and Zeiss, 2000). In current agriculture, usually yield maximization is prioritised over other ecosystem services provided by the soil such as nutrient cycling and carbon storage (Bender et al. 2016), key functions largely performed by soil organisms. Bünemann et al. (2018) review on soil quality showed how research to date has prioritised soil physical and chemical features as measures of soil quality, rather than biological analyses. This is likely due to the difficulties in studying these organisms, such as the difficult taxonomy combined with a paucity of specialists (Porco et al. 2014), opacity of the environment (Crotty et al. 2012), being mostly invisible or hidden within the soil matrix (Geisen et al. 2019) and general lack of funding available (Kim and Byrne, 2006).

The response of diversity, abundance, and function of soil organisms to soil management constitutes an important aspect of soil quality (Mbuthia et al. 2015) and life within the soil (i.e., soil biodiversity) in essence represents the soil's health (Paoletti, 1999). Soils are among the most abundant and diverse habitats on earth (Bender et al. 2016). This diversity in species and function is explained extensively in both the European Atlas of Soil Biodiversity (Jeffery et al. 2010) and the Global Atlas of Soil Biodiversity (Orgiazzi et al. 2016); as well as the recent report on the state of soil biodiversity (FAO et al. 2020). There is a greater biomass of soil fauna residing below-ground than normal stocking densities of livestock grazing above-ground (Crotty, 2021).

Together these organisms participate in functions important to the maintenance of soil quality. Throughout this review, soil biodiversity is discussed in terms of abundance as well as diversity; this is because biomass (abundance) is an indicator for biodiversity of the whole soil ecosystem. Both aspects – abundance and diversity are necessary for soil health and a fully functioning soil food web to perform ecosystem functions.

Review aims and hypothesis

This review will focus on soil improving cropping systems that reduce soil biodiversity loss, with a focus on temperate Europe. Here, SICS are defined as any agricultural management strategy that modifies the soil environment to improve the "health" or quality of the soil. A healthy soil is a sustainable soil that continues to produce profitable crop yields within agriculture, whilst also reducing biodiversity loss. If ecosystems are severely modified through intensive agriculture, then in theory SICS implementation is going to have a greater relative effect on reducing soil biodiversity loss than in more extensive farming systems, especially when leading to a more diverse landscape. However, even in a more extensive system, we hypothesise that SICS can still help to reduce soil biodiversity loss (*Figure 1*).

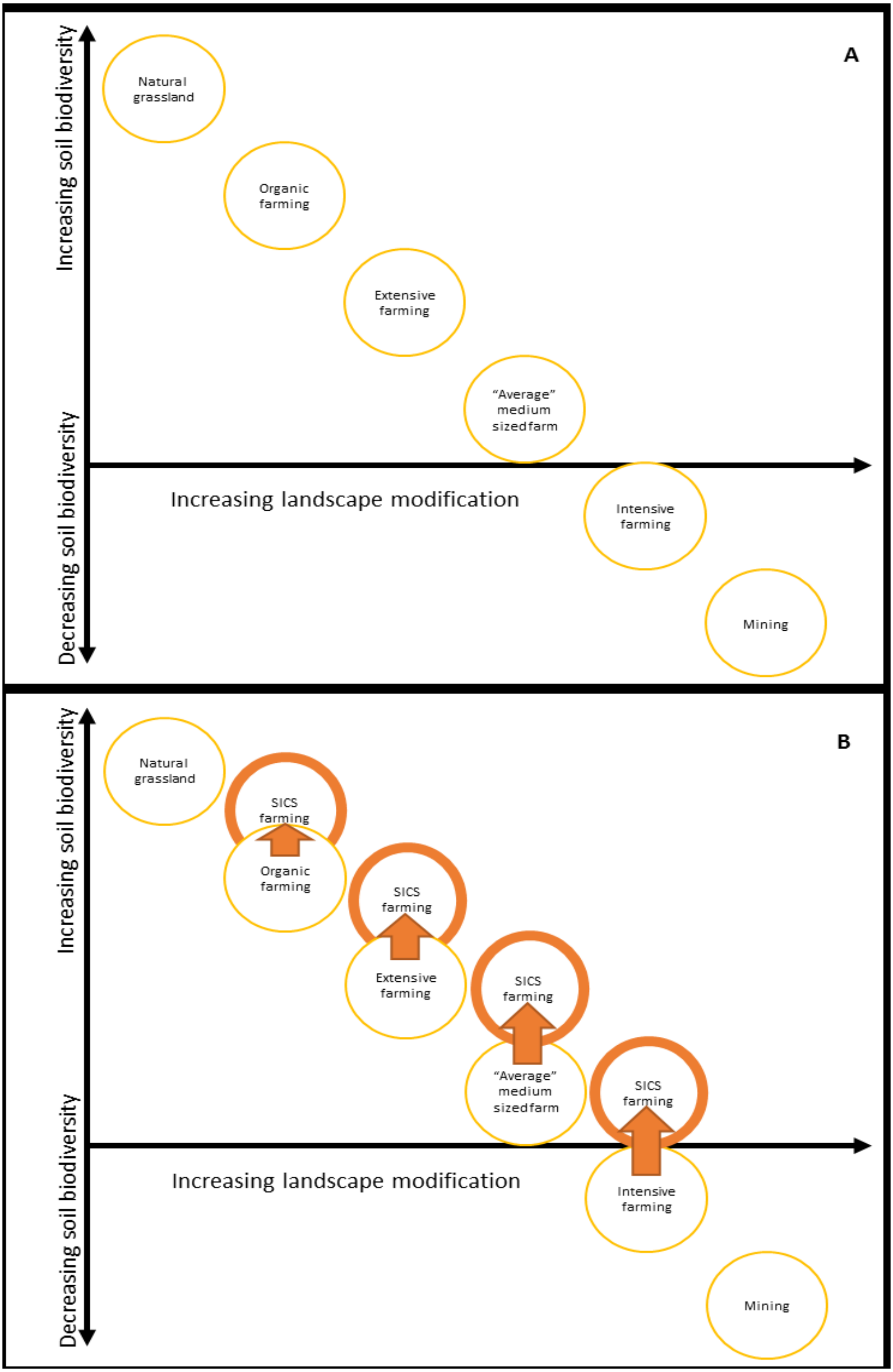

Figure 1. Visualisation of the effect of land management on soil biodiversity (**A**) and the effect soil improving cropping systems would have if they were implemented (**B**).

Key types	Cropping systems		
Crop	- *Cover crops* - Cash crops - Catch crops - Mixed cropping - Strip cropping - Companion cropping - *Intercropping* - Monoculture - Double cropping	- Crop rotation - Deep rooting crops - Vegetable crops - *Brassicacea* inclusion - Nitrogen fixing plants - Landraces (natives) - Permanent cropping (fruit) - Biodiverse mixes - Wild flower mixes	- Pollinator mixes - *Headland alternatives* - *Grass or grass/clover leys* - Fallow - Set aside - Buffer strip - *Agroforestry* - *Energy crops/forests*
Physical soil environment changes and water	- *Non-inversion tillage* - *Reduced tillage* - *Minimum tillage* - *Spike aeration*	- Soil conservation - Terracing - Soil stripping - Subsoiling	- Contouring - *Drainage management* - Irrigation management - Drip irrigation
Chemicals	- *Plant protection products* - Pesticide use - Soil amendments	- *BCSR amendment* - *Liming* - *Gypsum*	- Biofumigation - Solarisation - *Synthetic fertiliser*
Biological amendments	- *Organic fertiliser* - *Manure / slurry addition* - *Biodigestate* - *Mulching / living mulch* - Composting	- Residues - Compost tea - *Organic farming* - *Biochar* - Woodchip	- Mycorrhizal amendments - Bioaugmentation - Probiotics - Paludiculture - *Bio control*

Table 1. Overview of potential soil improving cropping systems. Cropping systems in italics are discussed more fully within this review.

There are many different types of SICS (*Table 1*) and these can be broadly grouped into five main categories – crop choice, physical/environmental change within the soil, chemicals, biological amendments and technology, but how they fit together within agriculture needs further study (*Figure 2*). Each SICS will affect biodiversity differently and different components of biodiversity will respond to different SICS – the aim of this review is to develop our understanding of the impact of these SICS on preserving soil biodiversity and reducing its loss. Most mechanisms that increase biodiversity with SICS are based on either change in (1) the distribution, quantity and quality of organic matter (OM) or (2) in improvement of habitat conditions for soil organisms (soil structure, aeration, and/or increased water holding capacity). Consequently, the focus of our review is to give an overview of the effect of different agricultural practices on functional groups of soil biota and soil biodiversity in general to depict the already available possibilities to manage agroecosystems in a more sustainable way by maximising biological functions providing ecosystem services.

Measuring biodiversity

Measuring biodiversity is incredibly challenging (Tibbett, 2015; Geisen et al. 2019), even more so in agricultural context (Lemanceau et al. 2015). Whilst blindly enhancing soil biodiversity infers random inclusion of many species (Bender et al. 2016), maintaining or increasing everything may lead to the inclusion of a greater diversity of undesirable organisms, e.g., pests (Simon et al. 2010) and weeds (Sanyal and Shrestha, 2008). However, a biodiverse agroecosystem might also decrease the opportunity for single, harmful, organisms to dominate (Wall et al. 2012). For more information on soil borne pathogens see Box 1.

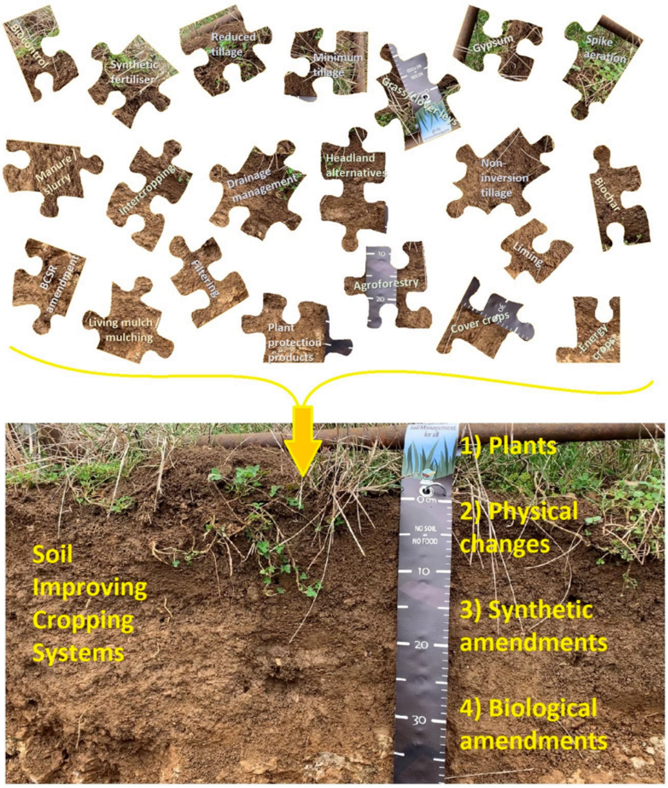

Figure 2. Soil improving cropping systems fit together like a jigsaw to improve the soil habitat for the organisms living within the soil. How they do this and by how much varies depending on the (SICS).

Box 1. Soil-borne Plant Pathogens

Soil-borne plant pathogens are part of the biodiversity within the soil, although are often not considered when soil biodiversity is discussed. These pathogens can survive a prolonged time within the soil, waiting for a host plant to grow. These organisms are various taxa including fungi, nematodes, chromists, protists and parasitic plants, and are found everywhere, both in agricultural and natural systems. All SICS that affect soil structure positively will reduce the threat of soil biodiversity loss, whilst also increasing the disease suppressiveness of the soil, reducing opportunities for opportunistic plant pathogens such as *Pythium* species to flourish. Once soil-borne plant pathogens appear at damaging levels within an agricultural system, it is necessary to control them as quickly and completely as possible; without destroying the rest of the soil biodiversity – although usually this is the unintentional consequence of soil-borne pathogen management. Commercial cultivars have been bred to be high yielding, whilst unintentionally becoming more susceptible to soil-borne pathogens, whilst years in nutrient rich conditions has also reduced crops dependency on their symbionts (Duhamel and Vandenkoornhuyse 2013). Currently, there are many projects investigating historic varieties and native relatives, to increase the naturally occurring resistance genes within a crop. Microcosm experimentation with different cultivars (including landraces) and earthworms, showed there was a large variation in responsiveness between cultivars – with a local landrace performing best with earthworms (Noguera et al. 2011).

There are a number of studies that have linked biodiversity increases with soil functions (e.g., Morriën et al. 2017, Wagg et al. 2014, Schäfer et al. 2019), however, this is rarely investigated in agricultural systems. The effect of cropping systems on the increase in abundance of a single group e.g., earthworms (Pelosi et al. 2015); although an important consideration, might be different to an increase in overall biodiversity. Furthermore, it is possible that an increase in biodiversity of one component in the food-web can lead to a decrease in diversity of another group through competition for resources or to have an add-on effect through feeding relationships (Morriën et al. 2017, Geisen et al. 2019) which makes the interpretation using only a single group of soil organisms more challenging. To monitor biodiversity, in principle all taxonomic groups need to be assessed (Griffiths et al. 2016), however, this is often impossible due to lack of expertise or prohibitively expensive. Therefore, within this review we limit ourselves to the relatively well-known groups of microbes (fungi and bacteria), meso- and macrofauna.

Overall, soil microbial biomass carbon accounts for 19 Gt globally (Crowther et al. 2019); this microbial biomass (C and N), is relatively simple to measure and can act as an indicator of management driven changes in diversity, abundance, and function (Kandeler, 2015). Arbuscular mycorrhizal fungi (AMF) form a symbiotic relationship with plants helping them to acquire nutrients and contribute to soil structure formation (Rillig and Mummey, 2006) making them one of the most studied groups. The composition of the AMF community is generally determined by plant species identity, plant diversity and soil nutrient status, especially P availability (Goldmann et al. 2020). Furthermore, soil disruption by mechanical management within agriculture (e.g., tillage) can be detrimental to both fungal hyphae and earthworm populations. Soil animals (i.e., Nematodes, Collembola, mites and earthworms) are important indicators of soil function and being further up the food chain than soil microbes, they integrate the physical, chemical, and biological properties related to their food resources; whilst due to their longer generation time (days to years) they are more stable temporally and not fluctuating as much due to nutrient flushes (Neher, 2001). Earthworms represent the largest component of animal biomass within the soil and are commonly considered to be ecosystem engineers (Blouin et al. 2013). Ecosystem engineers are organisms that affect the whole environment and either directly or indirectly have an impact on the other species inhabiting the same space (Jones et al. 1994).

It is not just the SICS that is important to understand, but the surrounding environment. Consequently, recommendations to achieve high levels of biodiversity in agroecosystems must consider specific pedo-climatic conditions or soil type. Bossio et al. (1998) gave a useful synopsis of the order of importance in evaluation of SICS: soil type > season > specific farming operation (SICS) > management system > spatial variation.

For example, earthworms are found to naturally occur at greater abundance in clay textured soils compared to sandy soil; however, compaction and waterlogging, which are also more likely to occur in clay textured soils, reduce the habitability of the environment for earthworms. Thereby introducing a SICS that reduces compaction and waterlogging risk could consequently improve earthworm abundance. Increasing earthworm abundance could also reduce the risk of compaction and waterlogging (as earthworms are ecosystem engineers and have a large impact on soil structure), leading to improvements in crop yields through soil biodiversity enhancement (*Figure 3*). Generally, all the different components of biodiversity in the soil are directly or indirectly affected by the cropping system (*Table 2*). However, each group of organisms may be affected differently, and it is thus important to understand how the mechanisms of agronomic practices affect these organisms and the functions they fulfil.

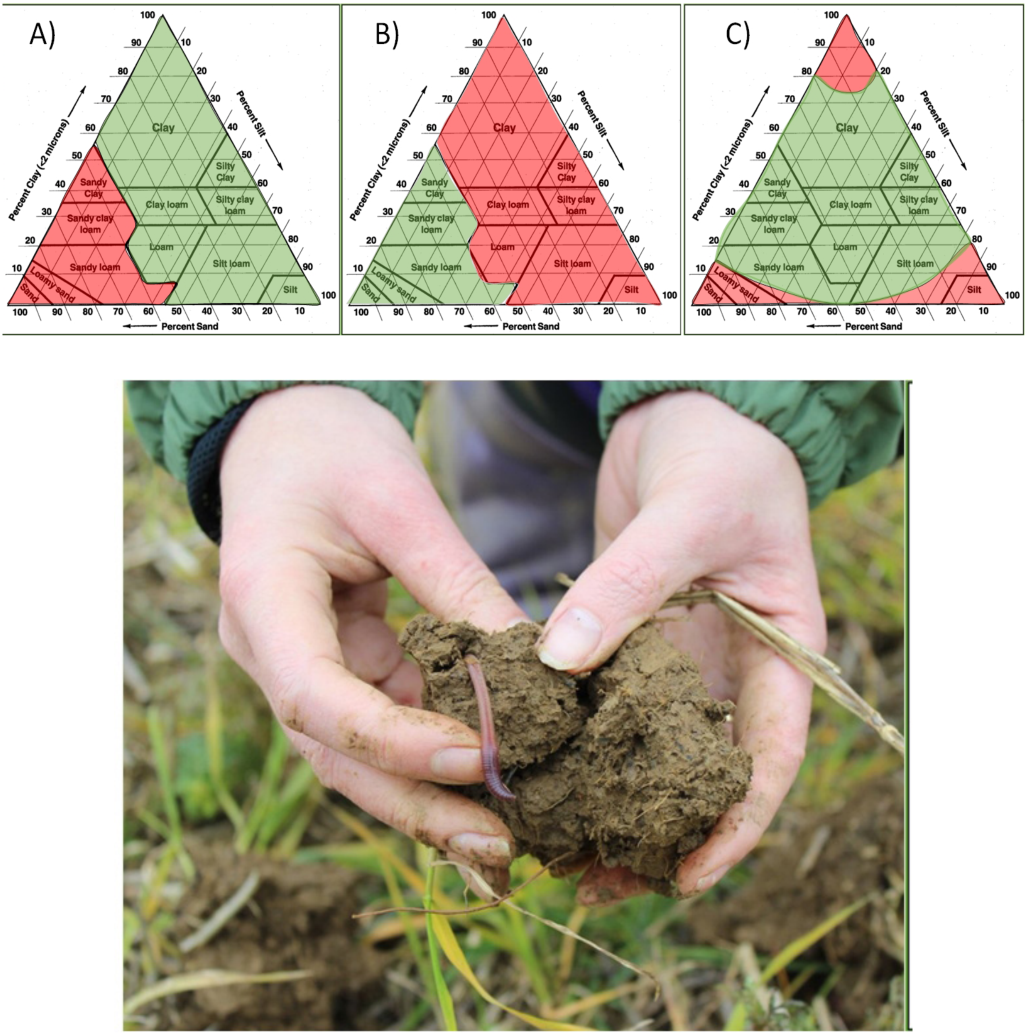

Figure 3. Conceptual diagram indicating A) abundance of earthworms in relation to soil texture; B) relative soil quality in relation to likelihood of waterlogging and compaction; and C) effect increased abundance of earthworms have on risk of waterlogging and compaction. [Green = high abundance of earthworms or low risk of waterlogging/compaction; red = low abundance of earthworms or high risk of waterlogging/compaction]. Soil sampling is shown below.

Organism	Effect on food and fibre production	How cropping system can affect organisms?
Bacteria (and Archaea)	- Increase nutrient availability - Promote plant growth - Reduce pathogens - Process/modify agrochemicals and xenobiotics - Change soil composition - Enhance soil structure **- Soil-borne pathogens**	- Increase food source (OM / amendments) - Flush of nutrients **- Change environment of soil (water/temperature)** **- Kill organism directly (pesticides)**

Organism	Effect on food and fibre production	How cropping system can affect organisms?
Fungi	- Cycling of essential nutrients - Promote plant growth - Increase N and P availability (through symbiosis) - Reduce pathogens - Process/modify agrochemicals and xenobiotics - Change soil composition - Enhance C allocation and build up OM - Decreased seedling mortality - Biocontrol against pests - Enhance soil structure (through hyphal growth and glomalins secreted by AMF) - Decomposition of plant residues (and subsequent release of nutrients). - **Soil-borne pathogens**	- Increase food source (OM / amendments / maintain plant residues / cover crops) - Flush of nutrients to provide burst of growth - **Change structure of soil (destroy hyphal network)** - **Kill organism directly (pesticides)** - **Remove host plant** - **Removal of residues of plant (food source)**
Protists	- Enhance microbial growth - Increase nutrient availability - **Soil-borne pathogens**	- Flush of nutrients - Increase food source (OM / amendments) - **Change environment of soil (water/temperature)** - **Kill organism directly (pesticides)**
Rotifers	- Contribute to nutrient cycling - Flocculation of bacteria	- Flush of nutrients - **Change environment of soil (water/temperature)** - **Anhydrobiosis (enables them to survive extended periods of desiccation)** - **Kill organism directly (pesticides)**
Tardigrades	- Enhance microbial growth	- Flush of nutrients - **Change environment of soil (water/temperature)** - **Anhydrobiosis (enables them to survive extended periods of desiccation)** - **Kill organism directly (pesticides)**
Nematodes	- Increase nutrient availability - Disperse bacteria and fungi - Reduce pathogens - **Soil-borne pathogens**	- Flush of nutrients - Increase food source (OM / amendments) - **Change environment of soil (water/temperature)** - **Change structure of soil** - **Kill organism directly (pesticides)**
Collembola	- Increase nutrient availability - Breakdown plant material, animal carcases - Faecal pellets contribute to soil microstructure and fertilisation. - Disperse microorganisms and nematodes. - Micro-ecosystem engineer (Brussaard et al. 1997) - Consumer of pathogens - **Host for parasites**	- Flush of nutrients - Increase food source (OM / amendments) - **Change environment of soil (water/temperature)** - **Change structure of soil** - **Kill organism directly (pesticides)**

Organism	Effect on food and fibre production	How cropping system can affect organisms?
Mites	- Increase nutrient availability - Breakdown plant material, animal carcases - Faecal pellets contribute to soil microstructure and fertilisation. - Disperse microorganisms and nematodes. - "Micro-ecosystem engineer" (Brussaard et al. 1997) - Consumer of pathogens - Host for parasites/parasitoids	- Flush of nutrients - Increase food source (OM / amendments) **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Kill organism directly (pesticides)**
Soil dwelling immature invertebrates e.g. beetle larvae, fly larvae	- Fragmentation and decomposition of organic material - Change pH of soil passing through gut	- Flush of nutrients - Increase food source (OM / amendments) **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Remove food source (plant species)** **- Kill organism directly (pesticides**
Other mesofauna (body width less than 2mm) e.g. Protura, Diplura, pseudoscorpions, beetles, spiders, Thysanoptera,	- Increase organic matter through burial of dung or carcasses - Predators of pests (pseudoscorpions, spiders etc)	- Flush of nutrients - Increase food source (OM / amendments) **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Remove food source (plant species)** **- Kill organism directly (pesticides**
Myriapoda (centipedes and millipedes mainly and Pauropoda, Symphyla)	- Excreta contribute to coprogenic humus	- Flush of nutrients - Increase food source (OM / amendments) **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Remove food source (plant species)** **- Kill organism directly (pesticides**
Enchytraeids	- Fragmentation and breakdown of plant litter - Enhance microbial growth, - Change soil structure (bioturbation) - Disperse of microorganisms	- Flush of nutrients - Increase food source (OM / amendments) **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Remove food source (plant species)** **- Kill organism directly (pesticides**
Root herbivorous insects / pests	**- Modifies plant performance** **- Yield losses** **- Changes plant physiology** **- Transmits diseases**	- Remove food source (plant species) - Introduce host food source - Change structure of soil - Kill organism directly (pesticides)
Earthworms	- Enhance microbial growth, - Change soil structure (bioturbation) - Disperse microorganisms - Aids sporulation / germination of fungal spores. - Improves water infiltration - Ecosystem engineer	- Flush of nutrients - Increase food source (OM / amendments) **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Remove food source (plant species)** **- Kill organism directly (pesticides**

Organism	Effect on food and fibre production	How cropping system can affect organisms?
Ants	- Enhance microbial growth - Disperse plant propagules - Change soil structure (bioturbation) - Increase porosity and drainage - Reduce bulk density - Ecosystem engineer	- Flush of nutrients **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Remove food source (plant species)** **- Kill organism directly (pesticides)**
Termites	- Enhance macroporosity and infiltration - Change soil structure (bioturbation) - Enhance microbial growth, - Ecosystem engineer	- Flush of nutrients **- Change environment of soil (water/temperature)** **- Change structure of soil** **- Remove food source (plant species)** **- Kill organism directly (pesticides)**

Table 2. Effect of organisms on food and fibre production overview (bold text indicates negative effects).

The inclusion of a SICS offers directly observable benefits for the soil ecosystem, but also indirect effects by modifying biodiversity-related functions. This can be illustrated taking as an example the inclusion of cover crops into the crop rotation (*Figure 4*). There are several direct effects of this management technique, both aboveground, for example, an increased C input into the system or erosion reduction, as well as belowground in the root zone, including the mineralisation of sparingly available nutrient pools by root-derived enzymes, or, for some plant species, rhizobial N fixation (*Figure 4*).

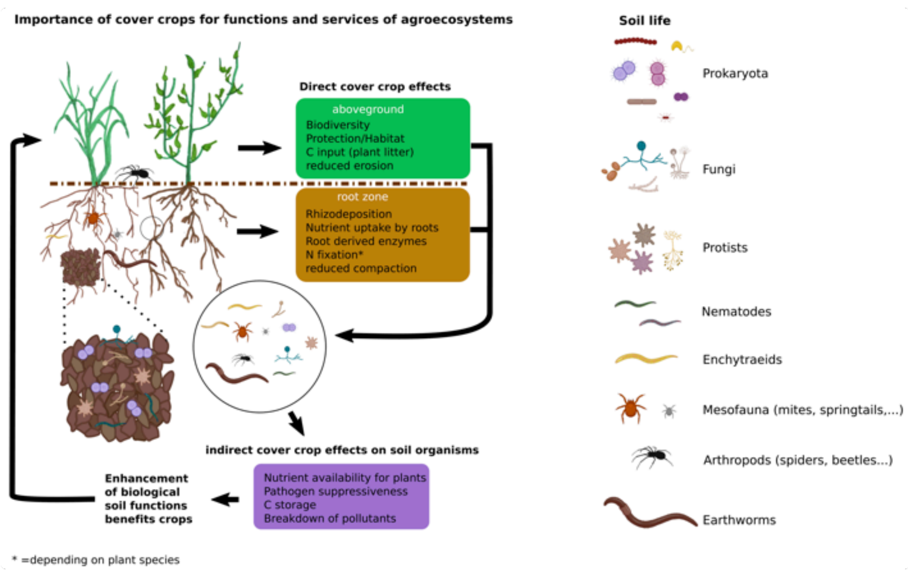

Figure 4. Importance of cover crops for functions and services of agroecosystems. Cover crops produce direct above and belowground effects which benefit the main crop, while also improving the habitat conditions for soil organisms. As soil biota are the drivers of several important ecosystem functions, the increase in biological diversity, abundance and activity enhances biological soil functions and agroecosystem services. On the right side is an overview of the different groups of organisms constituting soil life.

However, the presence of a living plant cover also improves the diversity, abundance, and activity of soil organisms, which control many processes, such as the availability of nutrients, suppression of pathogens, and C storage (the transformation of litter-derived C into soil organic matter). These enhanced biological soil functions benefit the crops grown on this field, leading to an improvement overall in the agroecosystem's performance.

There is often a discrepancy in the literature on the effects of soil biodiversity on plant productivity as soil ecologists tend to measure the effects of soil biodiversity on other ecosystem services than crop yield. Conversely, agronomists and practitioners often focus on yield measures without considering the role soil biodiversity has in maintaining soil quality and future crop yields. Therefore, there are large gaps in the literature, where these different focuses have rarely been considered, particularly in field-scale experiments. However even where yield and soil biodiversity are measured together, they are often not related directly (*Table 3*).

Location	System	Crop Performance	Soil biodiversity gain/loss	Reference
Argentina	Conventional agricultural management	Peanut-maize-sunflower rotation -> Maize grown during experimental period until end of year, before being grazed and residue ploughed under. Oat and sweet clover sown because of yield decline of maize and sunflower. ⇨ ***negative***	Collembola and pauropod reductions ⇨ ***negative***	(Bedano et al. 2006a)
		Peanut-maize-sunflower rotation -> suspected low yields of maize led to crop used as pasture for cattle during experimental period. ⇨ ***negative***	Mesostigmata and Oribatida reductions ⇨ ***negative***	(Bedano et al. 2006b)
	Good Agricultural Practice (GAPs) under no-till	GAPs (mixed crop rotation; cover crops; integrated pest, weed and disease management; nutrient restoration) in productive no till fields ⇨ ***positive***	Increases in litter and soil invertebrate abundance and modified faunal composition ⇨ ***positive***	(Bedano et al. 2016)
	Livestock	Sorghum with and without cover crops under no-till. Cover crops rye, vetch, and rye + vetch, rye + fertiliser. All cover crops with rye had similar aerial biomass whilst vetch produced significantly less ⇨ ***positive***	Cover crops increased litter and increased microbial biomass carbon and nitrogen. Soil litter disappearance is a good indicator of mineral N availability. ⇨ ***positive***	(Frasier et al. 2016)
Canada	Pasture	Grazing intensity increasing ⇨ ***neutral***	Mites less affected than Collembola; Prostigmata more abundant with grazing, Mesostigmata less abundant/ diverse with grazing. Overall diversity and abundance associated with reduced grazing intensity. ⇨ ***negative***	(Behan-Pelletier, 2003 and the references therein)
China	Maize	P-fertiliser application to maize did not affect yields due to large build up in soil prior to monitoring. ⇨ ***neutral***	Root length colonisation and arbuscular colonisation of maize roots was significantly affected by P-fertiliser application – higher rate decreased colonisation. ⇨ ***negative***	(Lui et al. 2016)

Location	System	Crop Performance	Soil biodiversity gain/loss	Reference
France	Conventional	Conventional vs no-till – Positive correlation between earthworm abundance and crop production, although contrasting effects on yields. ⇨ ***positive***	Direct drilling increases earthworm abundance and species diversity, but the beneficial effect of reduced tillage depends upon the species present and tillage intensity. ⇨ ***positive***	(Bertrand et al. 2015 and references therein)
Germany	Perennial energy crops	No difference in post-harvest C:N ratios (yields not discussed) ⇨ ***neutral***	Earthworm diversity, number and biomass significantly increased in newly introduced energy crops in comparison to maize. ⇨ ***positive***	(Emmerling, 2014)
Spain	Horticulture	Lettuce, Brussel sprouts, leaf beet and cabbage rotation; metaldehyde compared with biocontrol applications. For slug eradication, metaldehyde was only effective reduction of *Deroceras reticulatum*, whilst biocontrol only effective for *Arion ater*. ⇨ ***neutral***	Total numbers of all earthworm species, Collembola and Acari, were unaffected by treatments. ⇨ ***neutral***	(Iglesias et al. 2003)
Switzerland	Arable - Wheat	Two organic systems, one conventional with farmyard manure and one conventional with mineral fertiliser. Grain and straw yield higher in two conventional systems. ⇨ ***neutral***	Bacterivorous nematodes and earthworms most abundant in FYM receiving systems. Mineral fertiliser detrimentally affected enchytraeids and dipteran larvae. Spider abundance increased by organic management. ⇨ ***positive***	(Birkhofer et al. 2008)
USA	Arable - cover crops and tomato/corn rotation	Productivity highest after cover crops with high nitrogen content; significantly correlated with the structure of the soil fauna. ⇨ ***positive***	Cover cropped tomato/corn rotations had increased abundance of enrichment opportunist bacterial feeding nematodes ⇨ ***positive***	(DuPont et al. 2009)
UK (Scotland)	Pasture	Nitrogen fertiliser and lime addition to an upland grassland, increased above ground plant biomass and root returns to soil. ⇨ ***positive***	Nitrogen and liming reduced bacterial biomass (no change in fungal biomass). ⇨ ***negative***	(Murray et al. 2006)
UK (Wales)	Pasture	Nitrogen fertiliser application – inorganic or organic. Swards under organic management were botanically more diverse, although perennial ryegrass and white clover were predominant in all fields. ⇨ ***neutral***	Fungal PLFAs, Tardigrades, Acari and Nematodes were greater under organic management. Earthworm populations were smaller under organic management.. ⇨ ***positive***	(Yeates et al. 1997)

Table 3. Effect of agricultural management linked to crop performance and soil biodiversity at the field-scale.

Soil improving cropping systems

Several studies have shown that when the intensity of agricultural practices increases, the abundance and biodiversity of soil biota decreases (e.g. Tscharntke et al. 2005, Ponge et al. 2013, Bedano et al. 2016). Here, we highlight how agricultural practices can be harnessed to increase soil biodiversity whilst also promoting crop yield and sustainable intensification (*Figure 2*).

Crops

The biodiversity of soil organisms depends not only on the quantity and quality of food sources, but also on their spatial distribution (Müller et al. 2017, Ali et al. 2018, Pausch et al. 2018). Soil organisms are generally characterised by different life strategies: ones utilizing high pulses of (labile) OM resources (*r* strategist) and others using more recalcitrant organic compounds (*K* strategists). Consequently, crop selection, rotation or intercropping might induce a variation in root and exudate distribution within the soil profile as well as changes in the quantity and quality of OM in agroecosystems.

Crop selection and rotation

It is rare for soil to remain bare within nature, even during a fallow period within a crop rotation, plants will grow; whether these are rare arable plants or pernicious weeds is dependent on the seed bank. Soil biodiversity relies on the input of plants, as a food source and also to stabilise the soil habitat. Crop species differ in their ability to form AMF associations, together with N-fixing rhizobacteria the most studied soil microorganisms in an agricultural context, and in the benefits, they gain from this symbiosis (Kiers et al. 2011). Most agricultural crop species, with some notable exceptions (e.g., Brassicaceae, Polygonaceae and the Chenopodiaceae), are able to form AM fungal associations (Sylvia and Chellemi, 2001). However, the amount plants rely on their symbiotic mycorrhizal fungal partner is dependent on many factors, both biotic and abiotic. Since AM fungi are biotrophic, viability of AM hyphae gradually decreases in the absence of host plants such as during a fallow period. Harinikumar and Bagyaraj, (1988) in India reported 40% reduction of AM inoculum in field soil after leaving the land fallow for one season. Furthermore, long-fallow periods (>1 year) in northern Australia were associated with a decline in mycorrhizal colonization and AM sporulation in various crops (Thompson, 1987). Studies have shown that the longer the time the soil is left bare for, the larger the decrease in SOM (the only carbon source available during a fallow period); and also, the larger the detrimental effect on beneficial organisms like earthworms (Bertrand et al. 2015), however soil bacterial diversity has not been found to be affected (Hirsch et al. 2009). Leaving the soil bare for long periods of time also risks damage from other soil threats, particularly erosion.

Cover crops

Cover crops, catch crops and green manure refer to farming practices where plants are grown without removing the biomass, with the primary goal to maintain soil productivity and fertility, reducing erosion, and ensuring green cover throughout the year (Lehman et al. 2015). In general, the use of cover crops increases soil OM content and reduces soil compaction and can therefore be regarded as positive for soil biodiversity (Vukicevich et al. 2016), especially when multi-species cover crop mixtures are planted (*Figure 4*). Earthworm abundance and diversity is affected by cover crop species, for example Valckx et al. (2011) found ryegrass to be preferred over mustard, and phacelia and rapeseed residues were preferred over oats. Crotty and Stoate, (2019) found earthworm functional diversity changed dependent on cover crop mixture, with significantly more epigeic earthworms in mixtures with radish compared to bare stubble or oats and phacelia alone. Nematodes were also found to have twice the abundance in cover-cropped fields compared to fallowed (DuPont et al. 2009). In terms of increasing biodiversity, increases in biomass of one group of organisms will contribute towards an increase in total diversity, through stronger connections within the soil food web and the numerous species within that group. Overall, cover cropping definitely increases agroecosystem biodiversity and provided ecosystem services, but possible trade-offs and management complexity should not be underestimated (Daryanto et al. 2018).

Many studies consider the choice of cover crops that sustain the most diverse or most colonised AMF populations and how this subsequently affects the main crop (e.g., Hallama et al. 2019; Hannula et al. 2020), particularly in the response of P cycling (Reynolds et al. 2017) and as an additional N source (legumes). Adaption to site-specific conditions and management, including crop rotation and which cover crop species, need to be considered to maximise the benefits. The AMF-enhancing cover crops could constitute an alternative to inoculation (Cozzolino et al. 2013). Root and AMF hyphal fragments, which are important for early colonisation of the host plant, only survive for around six months in the soil (Tommerup and Abbot, 1981), therefore leaving the soil bare or with a non-mycorrhizal host can reduce colonisation rates of future crop hosts.

Intercropping

Similar to cover crops, the selection of species of plants in intercropping will affect the outcome. Intercropping with a mixture of non-mycorrhizal crops and mycorrhizal plants could help to sustain populations of AMF when the main crop is not mycorrhizal. In general, higher plant diversity leads to higher AMF diversity (Maherali and Klironomos, 2007). For example, tomato intercropped with leek showed 20% higher AM colonisation rate (for tomato) than tomato intercropped with tomato (Hage-Ahmed et al. 2013). Intercropping has also been found to support large earthworm populations through increasing the food supply throughout the year (Schmidt and Curry, 2001; Schmidt et al. 2003). These earthworm communities have even been found to be comparable to pasture and grass-legume leys with intercropping (Schmidt et al. 2001). However, besides the abovementioned positive potential, growing two or more crops simultaneously increases the complexity of management decisions (e.g., species combination or planting depth and date) and technical difficulties of harvesting and other field operations.

Grass/clover leys

Conversion from grassland to arable lowers the SOM content and stability of the environment, therefore introducing grass leys into a rotation will lead to positive SICS effects on biodiversity. For example, a two-year grass clover ley showed increases in earthworm abundance and diversity when compared to adjacent arable fields (Prendergast-Miller et al. 2021). Perennial fodder crops (e.g., grass, clover or lucerne) have been found to increase biomass and abundance of deep-burrowing (anecic) earthworms, improve soil structure and increase following crop yields (Kautz et al. 2010). Certain forage species are more favoured by certain soil fauna than others and can lead to increases in abundance and biodiversity (e.g., white clover instead of ryegrass (Crotty et al. 2015, Crotty et al. 2016)). Although, perennial ley crops in general have been found to increase earthworm numbers (Kautz et al. 2014). Native grasslands and plots where clover was grown had greater numbers of AMF compared to continuous wheat or barley plots (Menéndez et al. 2001). Cultivating clover after wheat restored AMF diversity and increased spore numbers over three years to resemble numbers in semi-natural grasslands (Oehl et al. 2003).

Agroforestry / agro-silviculture

It is well known that the perennial nature of most trees will have a profound impact on soil properties and hence, soil biodiversity, abundance, and function (Barrios et al. 2013) in any climate, although most research on the effects of agroforestry on soil biodiversity has focused on tropical regions. Biodiversity conservation is also one of the main reported ecosystem services/ environmental benefits of agroforestry (Jose, 2009). However, a meta-analysis by Torralba et al. (2016) focusing on European soil biodiversity (fungi and arthropods) did not find significant enhancement within agroforestry. Most trees form symbioses with ectomycorrhizal fungi, but some also have AMF as a partner. In studies performed in the (sub)tropics it has been shown that presence of trees in plots increased sporulation, mycorrhizal colonization of the crop species and number of AMF propagules in the plant roots (e.g., da Silva Sousa et al. 2013). In the recent review of Marsden et al. (2020) agroforestry had mainly positive effects on fauna abundance and diversity, when compared to cropland, and neutral or negative when compared to forests. It would be interesting to monitor a newly started agroforestry area to assess how the soil biodiversity changes with time – moving from an arable/grassland based soil to a woodland, as to date this has not occurred within European climates.

Energy forests / Biofuel crops

In areas with limited choice of rotation crops, energy crops may be a useful addition for widening crop rotations and to generate a more diverse landscape. Where energy crops are perennial, negative effects of soil tillage are alleviated. Abundance and diversity of earthworms found in energy forests was greater than neighbouring arable fields, due to the absence of tillage, increase in OM layer and environmental buffering (Lagerlof et al. 2012). Earthworms were also found to increase in perennial energy crops in comparison to silage maize (Emmerling, 2014), and even the non-native *Miscanthus* had positive effects on earthworm communities (Felten and Emmerling, 2011). However, *Miscanthus* has been found to have a negative effect on earthworm abundance and biomass when compared to undisturbed meadow (Brami et al. 2020). Most of the plants used as biofuel crops are fast growing and benefit from forming AMF especially in low nutrient conditions or during drought. A study conducted in Canada identified that the abundance of AMF was significantly higher in the herbaceous perennial grasses (switchgrass and *Miscanthus*) than in woody species (poplar and willow) used for biofuel production (Mafa-Attoye, 2020). In this study, the addition of chemical fertilizers did not affect the colonization of AMF. However, where natural grasslands have been converted to bioenergy crops, the impact of land-use change is the main driver of biodiversity change (Desirée et al. 2014).

Physical soil environment and water

Soils provide microhabitats for soil organisms (for example, within the drilosphere, porosphere, detritusphere, aggregatusphere, rhizosphere and mineralosphere (Beare et al. 1995, Kandeler et al. 2019), but might be severely affected by soil management. Only a limited number of soil organisms are able to change the physical environment of their habitat (like earthworms burrowing and mixing the soil). Consequently, any changes in physical soil properties by anthropogenic actions may improve or reduce the functionality of a habitat for soil organisms. SICS can contribute to habitat function improvements for a diverse community of soil organisms, for example, by changing the balance between pore connectivity (substrate transport and availability of food resources), oxygen and moisture availability.

Tillage reduction

Tillage is performed to prepare the seed bed for the next crop, weed and pest management, and to mix plant residues/amendments with the soil profile. During tillage, an increased porosity "unlocks" OM, increasing its decomposability providing a temporary boost to the bacteria and fast-growing fungi that utilise OM. However, this is followed by a reduction in activity, once the most available OM is utilised (Kraus et al. 2017). This increase in porosity could also reduce the amount of moisture stored within the soil profile, reducing the soil's drought resistance and limiting soil biodiversity that rely on soil moisture for movement (bacteria, nematodes) or bodily functions (breathing through their skin). The heavy equipment used for tillage may cause subsoil compaction, which in turn can affect rooting ability and water infiltration. Compaction can lead to inundated soils during times of heavy rainfall, threatening crop yields and soil biodiversity. There is a general agreement that tillage intensity influences microbial abundance and function (Ahl et al. 1999, Kandeler et al. 1999a and b, Li et al. 2020). The major outcome of different studies showed that reduced or zero tillage changed spatial distribution of residues (*Figure 5*) leading to a re-distribution of soil microorganisms within the upper 40 cm of the soil profile. Reducing tillage has been found to lead to higher carbon and microbial biomass in topsoils compared to conventional tillage systems (Tully, and McAskill, 2020).

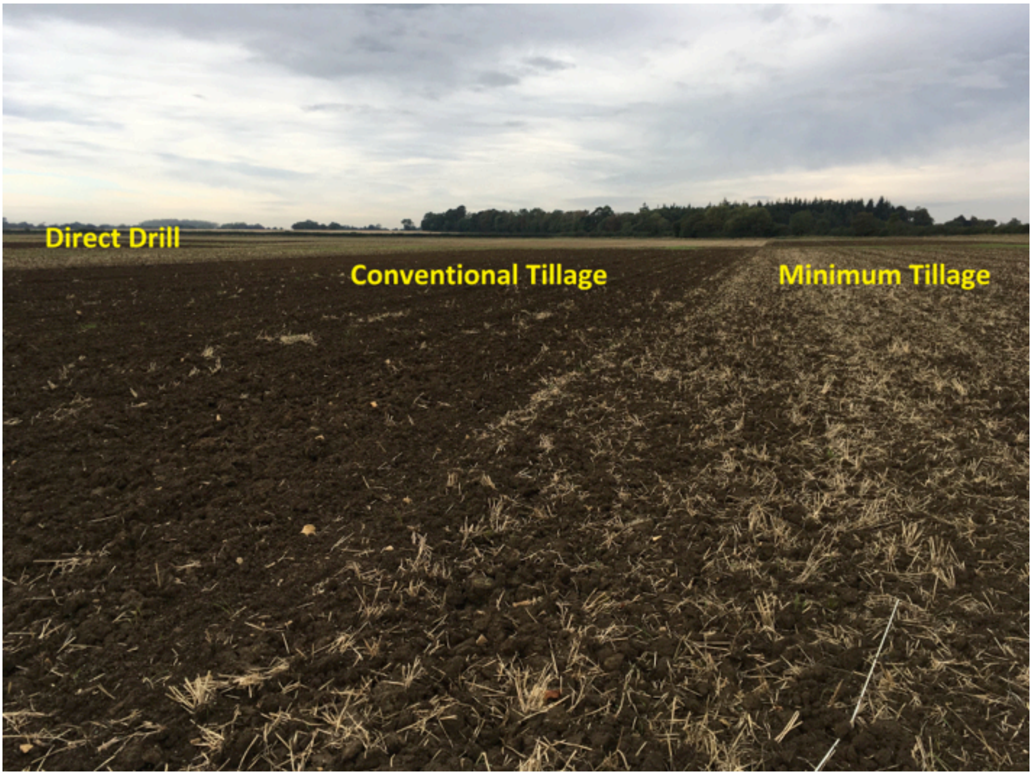

Figure 5. Photograph showing the difference in surface residue after three different kinds of tillage at the Royal Agricultural University long term experiment, Quarry Field, Harnhill, Cirencester. Tillage treatments visible in the photograph are direct drill, conventional tillage, and minimum tillage (labelled on photograph). Photograph taken by Dr Nicola Cannon (2019).

Kabir (2005) reviewed the impact of tillage practices on AMF (Arbuscular mycorrhizal fungi). Briefly, most of the studies found a reduction in the number of AMF taxa colonizing roots in systems with conventional tillage compared to reduced or no-tillage systems. There is also evidence for tillage changing community composition of AMF (Kabir, 2005; Jansa et al. 2003). Mechanisms for this include *(1)* the differences in tolerance to the tillage-induced disruption of the hyphae among the different AMF species; *(2)* changes in nutrient content of the soil; *(3)* changes in microbial activity; or *(4)* changes in weed populations in response to soil tillage (Jansa et al. 2003). The timing of tillage also influences AMF diversity – autumn tillage has been shown to cause reduced AM hyphal viability, whereas spring tillage had little effect (Kabir et al. 1997a, Kabir et al. 1997b). This is likely caused by the hyphae being detached from the host plant in the autumn, whilst in spring AMF is mostly found as spores.

All soil fauna impacted by ploughing will benefit from no-till or reduced tillage management (Orgiazzi et al. 2016). Frequent studies have shown earthworms to be negatively affected by tillage, as found in the global meta-analysis by Briones and Schmidt (2017). The detrimental effect of tillage on earthworm community composition and abundance is often dependent on the intensity (Emmerling, 2001) and frequency – the less intensively the soil is disturbed, the less harmful tillage is for earthworms (Bertrand et al. 2015). Tillage is known to be detrimental to other soil fauna including Collembola (Bedano et al. 2006a), Acari (Bedano et al. 2006b) and to a lesser extent nematodes (Fiscus and Neher, 2002), overall impacts of tillage regime on soil biota seem to be group-dependent (van Capelle et al. 2012). Tillage is commonly used within organic farming, negating some of the benefits that soil biodiversity should be deriving from organic amendments and practices. Promoting occasional reduced tillage within organic systems has been shown to have immediate positive effects on earthworm populations (Moos et al. 2016). Tillage is often used as a simple method to lessen surface soil compaction (although could be transferring the problem to the subsurface, creating a plough pan). Plants grown on compacted soil are exposed to a multi-stress environment (Colombi and Keller, 2019) limiting soil fauna's ability to access water and food, as well as changing the habitable pore space the fauna live within. Spike aeration or the use of different tine options to alleviate compaction in wheelings of arable crops (Niziolomski et al. 2016) or within pasture (Cournane et al. 2011) has the potential to improve soil structure, whilst also reducing runoff, phosphorus, and nitrogen losses (DeLaune et al. 2013). These methods have the potential to reduce compaction without disturbing the whole soil environment to the same extent as tillage. However, to date the impact of these other soil improving cropping systems on soil biodiversity loss has not been monitored.

Drainage management

Drought decreases soil water content and has been found to decrease microarthropod species richness, whilst irrigation has been found to increase microarthropod species richness (Tsiafouli et al. 2005). Drainage and irrigation have been shown to encourage multiplication of the more robust species of the Acari (Prostigmata and Astigmata) (Behan-Pelletier, 2003). Oribatida have also been found to increase in abundance and species richness with increasing soil moisture (Jakšová et al. 2020). Soil drainage has also been found to impact the community structures of actinomycetes and pseudomonads (Clegg et al. 2003).

The porosity of the soil will influence the likelihood waterlogging will occur, with a large fraction of micropores within the soil profile leading to poor aeration and a higher risk of waterlogging; whereas a high proportion of conducting continuous macropores will lead to the soil drying out more rapidly, effecting the soil habitat for the biodiversity residing within it. Water infiltration is an ecosystem service the soil provides, which can be affected by poor soil management and when the infiltration rate is low, it can lead to surface runoff, erosion, and flash flooding. Earthworms as ecosystem engineers can change the water infiltration rate of a soil through their burrowing activity and the creation of permanent burrows (Crotty, 2020). Research establishing and quantifying the relationship between earthworms and water infiltration capacity of soils has been occurring over the last fifty years (Griffiths et al. 2018). Controlling the drainage status of soil is necessary for preserving a suitable soil structure (Mueller et al. 2013) for soil biodiversity and crop growth.

Chemical amendments

All chemical amendments (pesticides, synthetic fertilisers, other chemical amendments) have an impact on soil biodiversity, irrespective of target pest or reason for applying (Karpouzas et al. 2014). The likelihood of pesticides affecting non-target soil biodiversity is dependent on mode and timing of application, as well as the climatic conditions at the time (and after) (Karpouzas et al. 2014). Due to the different ecological functions and preferences of the different taxa residing within the soil, some chemical amendments (e.g., liming or synthetic fertilisers) may promote the retention of some groups at the deficit of others. These conflicts in requirements by soil organisms indicate that more work is needed to understand which SICS might be best to reduce soil biodiversity loss.

Plant protection products (pesticides)

All pesticides have wider implications than their target pest (Crotty, 2020). For example, insecticide seed dressings or granules will also reduce soil faunal populations, including springtails, mites, beetles, fly larvae, psocopterans, nematodes and earthworms (Pisa et al. 2017). Molluscicides have been found to be deleterious to non-target soil invertebrates to a certain extent (e.g., metaldehyde (Santos et al. 2010) or ferric phosphate (Langan and Shaw, 2006; Edwards et al. 2009)). Reducing the number and amount of slug pellet applications, and following manufacturer's instructions, will reduce the risks of soil biodiversity loss.

In general, nematodes can be controlled using nematicides, while soil fungicides are much less available. Nematicides have been shown to impact all nematode trophic groups (Timper et al. 2012), this includes those nematodes that predate on plant pathogens (Hofman and Jongebloed, 1988), as well as the other nematode functional groups. This may have a lingering effect due to the changes in the soil food web of other invertebrates over the same time-period (niche filling). Herbicides have also been found to negatively affect soil fauna – for example glyphosate has been found to decrease root mycorrhization and AMF spore biomass (Zaller et al. 2014); inhibited bacterial growth (Aristilde et al. 2017); and reduced earthworm activity and reproduction (Gaupp-Berghausen et al. 2015). Miller and Jackson (1998) showed that weeds are important hosts maintaining AMF when growing non-mycorrhizal crops, forming a mycorrhizal bridge between crops. There is a significant body of literature about the negative side-effects of applying soil pesticides (Siepel, 1996, Firbank et al. 2008). Therefore, it is important to create an integrated pest management strategy, applying pesticides through "spot application" or when an outbreak is greater than the "economic threshold" of the damage occurring. In general, the use of synthetic chemical pesticides is increasingly criticized because of residues remaining in the environment and food chain, and because of the threat to biodiversity. Researchers need to help farmers by developing state-of-art automated and digitally networked technologies and find solutions so that synthetic chemical pesticide use can be abandoned in the future. At the same time, it might still be required to use mineral fertilization to guarantee high biomass yields. These cropping systems without the use of pesticides, but with mineral fertilizers represent a complete reorientation in agricultural production of food and feed.

Other chemical amendments

Soil pH has been found to be the single most significant edaphic variable to predict bacterial community composition (Fierer and Jackson, 2006) and thus can affect fungal and bacterial feeding organisms – cascading through the soil food web. Reducing the acidity of soil through liming has been found to promote earthworm abundance in the field over time (Hirth et al.

2009). However, some studies have found other soil taxa to be detrimentally affected (e.g. fungi (Murray et al. 2006, Hannula et al. 2021), Collembola (Chagnon et al. 2001); and Acari (Hagvar and Amundsen, 1981)). Liming is an appropriate measure to control *Plasmodiophora brassicae*, the causal agent of club root on brassicas. In a recent study, long term liming was the single agricultural treatment that caused the biggest change in soil fungal community structure (Hannula et al. 2021). The addition of gypsum (mined or flue gas desulphurised), is another amendment that has been found to reduce earthworm abundance and biomass in some instances (Chen et al. 2014). These conflicting results on the effects of liming on different forms of soil biodiversity, indicate more research is needed on the impact of liming and other soil amendments on soil biodiversity loss.

Industrialised animal production has led to large increases in the release of antibiotics to the soil environment. Besides potential shifts in the soil microbial community, the emergence of antibiotic resistances is a major concern for public health (Cycoń et al. 2019). Other pollutants, such as heavy metals (Thomas et al. 2020) and pesticides (Kurenbach et al. 2018) might also cause similar effects. It is also important to note, that the soil microbial community is a major reservoir for novel antibiotics (Ling et al. 2015). The use of plastics in agriculture and horticulture, as well as the use of municipal waste compost results in large amounts of plastics in the environment. Microplastics are considered an emerging threat to soil biodiversity (Tibbett et al. 2020). The effect of large amounts of chemically quite diverse plastics and their decomposition products on the soil biota is currently under investigation (Schöpfer et al. 2020, Li et al. 2021). For example, microplastic particles (smaller than 5 mm) differing in their shapes (spheres, fibres, and fragments) may harm soil organisms (Bläsing and Amelung, 2018).

Synthetic fertilisers

AMF have been described as natural biofertilisers (Berruti et al. 2016), however most farmers do not consciously rely on this biological function. Negative effects of synthetic fertiliser application on soil biodiversity can be due to the increased soil acidification. Additionally, the AMF community is usually less diverse in agricultural systems due to the over-supply of P, reducing the dependence of crop plants on the symbiotic mutualisms with fungi (Liu et al. 2016). Also, the form in which fertilisers are added has an influence on the AMF community and organic fertilisers are thought to be more favourable for AMF.

Application of fertilisers can have an effect on soil faunal populations, this can be both positive (application of a food source for soil organisms to utilise) or negative (soil acidification – changing the pH of the soil to have less hospitable conditions) (Crotty, 2020). The use of inorganic fertiliser has been found to reduce the abundance of Collembola, Oribatid mites, Enchytraeidae, and earthworms (Siepel, 1996; Yeates et al. 1997), although direct effects are limited. Earthworm abundance and diversity increases with OM input and content of soils, therefore when an inorganic mineral fertiliser source is used instead of an organic, variety numbers are reduced (Lapied et al. 2009). Nematode abundance was also found to be reduced when inorganic fertiliser and pesticide inputs where combined, compared to organic production combined with minimum tillage (Overstreet et al. 2010).

Biological amendments

Many biological amendments have large-scale benefits to soil biodiversity in general, however they can also involve the greatest changes within a farming system. For example, the change from conventional to organic agriculture is not just a change in one practice (unlike a change from ploughing to direct drilling where all other actions remain the same); this is also not going to occur across all farming systems. Organic farming is often promoted as a way to enhance the long-term sustainability of modern agriculture whilst decreasing environmental impacts (Bedoussac et al. 2015). However, changing large areas from conventional to organic farming will not maintain current yields, leading to an increase in the area farmed (Smith et al. 2018), increasing greenhouse gas emissions (Smith et al. 2019). Although other studies have found that large-scale conversion to organic farming could improve food security and sustainability on a global scale (Wilbois and Schmidt, 2019; Röös et al. 2021).

Soil biodiversity is known to increase when more natural amendments and practices occur, along with other soil improvements (increased SOM, water holding capacity, reduced erosion). However, given the current market pressures and agricultural policies, it is naïve to expect the majority of farmers to change in this way in the short term; a more practical option would consist in encouraging the use of biological amendments in conventional agricultural practice. Farmers should consider organic "farm waste" as valuable resources, and their application as biological amendments could improve soil biodiversity, whilst maintaining high yields and profitability.

Other biological amendments have been tested in microcosm experiments (e.g., biochar, mycorrhizal additions, microbial inocula), which do not represent field conditions and have not focused on the impact of these additions on native soil biodiversity – this research gap needs to be further investigated before these SICS can be invested in at the field scale (Bradáčová et al. 2019, 2020, Eltbany et al. 2019). However, a recent study by Clocchiatti et al. (2020) did show that the addition of deciduous wood sawdust and paper pulp stimulated an increase in fungal biomass within arable soil in microcosms – suggesting these biological amendments will help soil biodiversity through food addition and stabilisation of the environment, warranting further investigation.

Organic fertilisers

The application of organic fertilisers, like farmyard manure or slurry, benefit the soil biota more than mineral fertilisers, partly because the organic matter represents a source of mineralisable nutrients. However, there can be issues with the organic fertiliser containing heavy metals, antibiotics, or pathogens. The application of animal manures as nutrient sources has generally been found to increase the abundance and activity of soil biota (particularly nematodes, Collembola, Acari and earthworms) (Altieri, 1999; Birkhofer et al. 2008, Wu et al. 2013, Orgiazzi et al. 2016). Organic amendments will stimulate soil microbial activity, thereby potentially increasing the disease suppressiveness of the soil as soil-borne pathogens are out-competed. For example, long-term application of swine slurry, whilst maintaining productive crop yields, also influenced AMF and their products (glomalin) in the soil environment (Balota et al. 2016), likely through changes in soil aggregation. Utilisation of organic fertilisers has the potential to convert a farm waste into a benefit (Crotty et al. 2018), making the farming system more sustainable, as well as acting as a SICS to retain soil biodiversity.

Anaerobic digestate has a decreased pathogen load in comparison to manure/slurry, due to the digestion process, pathogen reduction increases if the process is thermophilic (Insam et al. 2015). The addition of anaerobic digestate (in the form of labile organic matter) provides a large substrate source for microorganisms and has been found to increase microbial biomass within the soil (Nkoa, 2014). Digestate does not appear to have a negative effect on earthworms exposed directly to it at low concentrations (Pivato et al. 2016), although negative effects were found at high concentrations (Rollett et al. 2020).

Biochar amendments

There have been few studies on the effect of biochar on soil organisms and even fewer in temperate soils (Mackie et al. 2015). Those that have investigated the addition of biochar have shown that microbial biomass is increased (Lehmann et al. 2011, Bamminger et al. 2016). However, AMF abundance did not increase if there was an already abundant nutrient supply (i.e., in agricultural environments). Experiments manipulating the number of earthworms and biochar showed that rice yields increased the most when both were added together (Noguera et al. 2011); however, this does not discuss how earthworm populations are affected at the field scale. Currently, the application of biochar is often combined with compost amendments to be sure that biochar with its high sorption capacity does not interfere with plant uptake of nutrients. Research is ongoing and there are concerns that the application of recalcitrant biochar entails risks, as potential negative effects would be persistent for a long time.

Mulching

Mulch is usually plant material that is partially decomposed left on the soil surface to form a cover, it can be a living mulch, green residue that has been allowed to die back or applied organic material. The mulch provides a large surface area for pesticide sorption and/or can be used by soil microorganisms as co-substrate for co-metabolic degradation of pesticides (Aslam et al. 2018). In addition, mulch reduces water infiltration rates, and soil erosion by creating an organic barrier on top of the soil surface. Organic mulch biomass is a source of C and nutrients required for soil biological activity (Orgiazzi et al. 2016). A variety of mulches can be used in-row in perennial horticultural cropping systems. These mulches have been found to increase the abundance of protozoa, bacterivorous nematodes and enrichment opportunistic nematodes in comparison to bare ground or polyethylene covering (Forge et al. 2003). Long term use of living mulch and organic fertiliser have been found to increase earthworm populations by between 1.5-2.3 times greater than conventionally fertilised populations (Pelosi et al. 2015). Mulching can also reduce the spread of some air-borne pathogens (Litterick et al. 2004) e.g., Botrytis in strawberries.

Mycorrhizal amendments

The use of commercial (laboratory grown) inoculants containing non-resident AMF is an emerging technology in field crop production, especially in systems with lower input of P-containing fertilisers. Adding AMF to soils can enhance crop yields and protect plants from biotic and abiotic stresses (Boyer et al. 2015). For example, AMF addition has been found to alleviate the stress of soil compaction in wheat and corn (Miransari et al. 2007, Miransari et al. 2008). However, carrying out an open-field, extensive inoculation treatment is often technically impractical, economically prohibitive and is advised only if the native AMF population is not present or has very low diversity, to avoid possible negative effects on the soil biota. Indeed, the effects of inoculants on native soil populations is largely unknown and needs to be understood before large scale amendments are done (Rodriguez and Sanders, 2015). Adding an AMF inoculum has been shown to be an effective and economical option to restore degraded soils with little of its native biodiversity left (Berruti et al. 2016). However, minimal research has occurred on the effect of mycorrhizal amendments on soil biodiversity in general. More research is also necessary to address inoculation-related biosafety concerns (Mitter et al. 2021).

Biocontrol

Addition of nematodes as a biocontrol agent in mollusc reduction has been shown not to affect earthworm or mesofauna abundance (Iglesias et al. 2003); although there can be some problems with efficacy in comparison to metaldehyde or iron phosphate (Rae et al. 2009). Two biocontrol agents *Streptomyces griseoviridis* and *Trichoderma* spp., are regularly used in protected cultivations against a range of fungal and chromist soil-borne pathogens. However, these products are unable to control existing high populations of pathogens. Brassicacea-based (allelopathic) management strategies, are a soil biodiversity-friendly alternative to nematicides, and have been shown to be effective at managing the top-three economically important nematode pests; root-knot (Meloidogyne), cyst (Heterodera and Globodera) and lesion (Pratylenchus) nematodes (Fourie et al. 2016). Acting as a form of biofumigation, brassica residues form toxic compounds (isothiocyanates) during their decomposition (Larkin and Griffin, 2007). Hatch crops (particularly *Solanum sisymbriifolium* and *Tagetes*) are another non-chemical method that are often used in Europe to combat potato cyst nematodes and Pratylenchus. AMF can also be considered to act as a type of biocontrol agent, as well as exchanging carbon with the host plant it can also help to defend the plant from pathogens (Johansson et al. 2004).

Discussion

Agricultural intensification (soil tillage, increased mineral fertiliser usage and crop diversity reductions (Postma-Blaauw et al. 2012)) has been shown to affect abundances of taxonomic groups with larger body sizes (earthworms, enchytraeids, microarthropods and nematodes) more negatively than smaller-sized taxonomic groups (protozoans, bacteria and fungi) (Postma-Blaauw et al. 2010). However, the effect agricultural intensification has on the whole soil food web needs to be considered, global studies of the threat to soil biodiversity show there are large areas at risk (*Figure 6*).

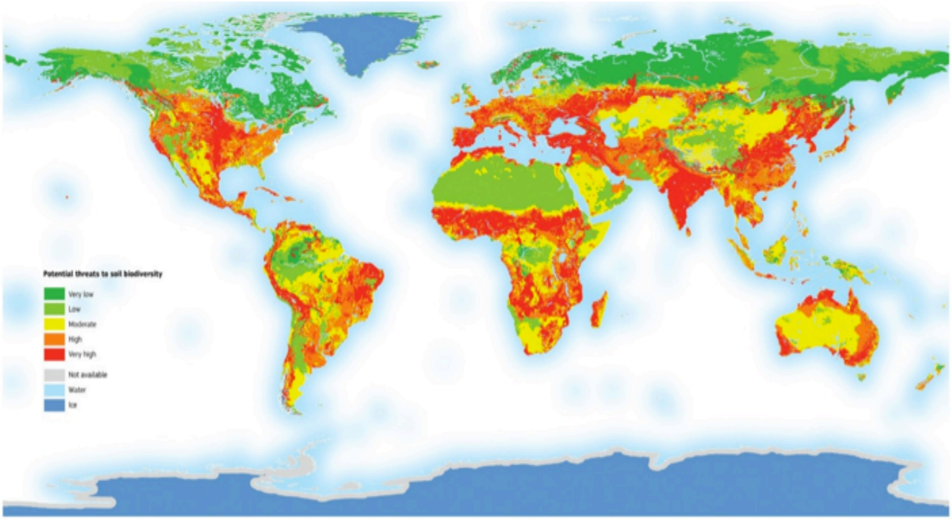

Figure 6. Map of global threats to soil biodiversity (Orgiazzi et al. 2016)

Intensively managed agricultural soils are among the poorest soils in terms of biodiversity of microbes and fauna, and the lack of diversity is likely to reduce the capacity of the soil to function (Bedano et al. 2006). Measures to extensify agricultural practises need to be taken in order to increase species diversity and the connections between them (Morriën et al. 2017) and reach a 'healthy' well-functioning soil, this is essential for the provision of ecosystem services. There should be a holistic approach to maintain biodiversity focusing on the inclusion of many groups of soil organisms and their interactions. From a methodological viewpoint, we can detect relative shifts, e.g., using molecular markers, but face difficulties giving absolute abundances and connecting them with ecological relevance. An urgent measure would be the incorporation of soil biodiversity measurements in national soil quality monitoring schemes. A two-way strategy combining emerging cutting-edge methods, like metabolomics (Withers et al. 2020), with "ground truth" relevant for practitioners, such as visual soil assessment and spade tests (Junge et al. 2020), as the provided summary parameters are tightly related to soil biodiversity.

Increasing soil biodiversity could also be thought of as a soil improving cropping system by itself; numerous studies (e.g., van Groenigen et al. 2014 and the references therein; Bender and van der Heijden, 2015) found that increasing soil biodiversity can increase crop yields and decrease nutrient losses, being therefore directly linked to the sustainability of agriculture. However, as seen in *Table 3* this view has not been widely considered by academics researching agricultural cropping systems. Going forward, academics researching soil biodiversity should try to measure yield within experiments assessing relevant farming techniques and report results also in similar terms as agronomists – to emphasise the importance of soil biodiversity to sustainable agriculture. Interestingly, advocates of emerging alternative agriculture movements, i.e., agroecology, conservation, or regenerative agriculture, base their claims of an increased sustainability of their systems frequently on alleged positive effects of increased biodiversity.

There are substantial knowledge gaps when it comes to practical recommendations to farmers, despite noteworthy potential synergies of the combinations of different SICS. For example, cover crop management is key for successful conservation agriculture (Mirsky et al. 2012), but limited management experience of this system results in higher risks and the possibility to make mistakes with these knowledge-intensive systems (Zikeli and Gruber, 2017). Also, the potential detrimental effects on soil biodiversity of an increased use of herbicides in response to the weed pressure in no-till systems may play a role in the mixed results of field experiments (Kremer and Means, 2009; Nguyen et al. 2016) and weed control is one of the greatest problems of herbicide-free no-till systems (Zikeli and Gruber, 2017). In practice, farmers that experiment with no-till techniques often adopt a modified direct seeding approach, using shallow non-inversion tillage in emergency situations (*Figure 5*), e.g., when the cover crop did not emerge due to unfavourable climatic conditions. This example illustrates that every management technique of a SICS comprises a wide spectrum of possibilities, making absolute recommendations difficult, but offering opportunities to fine-tune and adapt SICS to the local conditions.

Figure 7. Photograph showing example of diversity extracted from a soil core. Photograph taken by Dr Felicity Crotty, 2010, (this photograph was the winning entry in the BBSRC Science Photo Competition – Agriculture, Food, Diet and Health Category).

It is often suggested that there is a greater diversity living below-ground than there is above-ground, with soil being referred to as "the poor man's tropical rainforest" (Giller, 1996) (*Figure 7*). It has been estimated that there are over 12.8 quadrillion (10^{12}) soil invertebrates in the top 8 cm of soil across the UK (Countryside Survey, 2007). However, it is not just the biodiversity that is important but also the interconnectance of the soil food web. The feeding relationships among the soil fauna and microbes form an intricate soil food web (Hunt et al. 1987) which ranges over multiple scales (micro, meso and macro) (Swift et al. 1979) with orders of magnitude differences in size between organisms (*Figure 8*).

Figure 8. Photograph showing difference in size of organisms living within the soil. Photograph taken by Dr Felicity Crotty, 2010, shortlisted Microflora and Mesofauna category – Global Soil Partnership and FAO, Soil Biodiversity Photo competition 2020. On the right is a pseudoscorpion (moss neobisium), a tiny predator that lives within the soil and litter layer, ensnaring a Symphypleona springtail (Collembola), part of the mesofauna, within its pincers.

Conversely, due to the large diversity of species there is also a considerable amount of functional redundancy (i.e., the same function is being performed by multiple distinct groups of organisms). This functional redundancy creates an inbuilt resilience of soil biodiversity to perturbations (Bengtsson, 2002). The diversity, abundance and complexity of the soil make understanding the interactions and effects of SICS multifaceted, with organisms interacting and affecting each other, as well as reacting differently to the different SICS. In view of the multiple ecosystem functions of soil biota, a holistic approach of increasing biodiversity through agronomic management as opposed to a reductionist approach focusing on single species or inoculation may be more appropriate (Fester and Sawers, 2011). Several groups, including mycorrhiza can be considered "umbrella" species for agroecosystems, as several management techniques that enhance these groups have other beneficial effects on other species and in the agroecosystem. Therefore, a broader approach by embracing agroecology, where farmer–scientist alliances co-create and exchange knowledge, transforming the research system of agronomists and ecologists (Levidow et al. 2014), while producing relevant results for agriculture might allow the development of more sustainable management systems. To enable better research, an interdisciplinary approach is needed, to consider soil biodiversity (ecologists) and what happens if it is lost in relation to crop yield and sustainability (agronomists).

Soil organisms can improve the soil's capacity to function, through nutrient cycling, changing the structure of the soil – increasing porosity, reducing compaction as well as redistributing nutrients (*Table 2*; *Figure 4*). Without soil organisms, there would likely be reductions in crop yields, however lower crop yields due to reduced soil biodiversity are often masked by increased fertiliser (or other inputs) applied. Changing the focus of agricultural management to include soil biodiversity will reduce the risk of soil biodiversity loss (*Table 1*; *Figure 1*). However, it is important to consider the whole soil environment as soil type / texture will also have a large effect (*Figure 3*). In most cases, soil properties (i.e., type, texture) and climate dominate the abundance and diversity of soil biota, but constitute fixed properties, while management can be adapted to improve the provision of ecosystem services.

Within this review, we have focused on a range of organisms (mycorrhiza to earthworms; *Figure 7 and 8*), through this range of scale and lifecycle we can gauge the impact of agricultural management and have postulated potential SICS that can reduce the risk of soil biodiversity loss without compromising yields (*Figure 2*). Many of these SICS also reduce the risk of other soil threats (e.g., soil organic matter loss, soil erosion, soil compaction). These threats are all reduced if the whole agricultural management system is considered rather than just short-term yield benefits that won't last for future farming generations. Therefore, external benefits for society, as water, soil, and biodiversity protection, as well as an increased C sequestration, which are currently not reflected in the market value of the crops, need to be considered when establishing the price of an agricultural production (Dendoncker et al. 2018).

Conclusions

Ecological studies have shown that greater plant diversity suppresses plant disease and promotes increased overall resistance and resilience of the ecosystem; however, this has not been shown in relation to soil biodiversity and therefore these theories need rigorous testing in agricultural settings at field scale (Vukicevich et al. 2016). Also, the links between different ecosystem services, especially the trade-offs and synergies with biodiversity need to be investigated. As biodiversity affects other ecosystem functions, agroecological management techniques that promote soil biodiversity and soil biological functions, indirectly affect other ecosystem services. This review has highlighted that agricultural research and soil biodiversity research needs to be brought together, so that the impact of soil biodiversity loss can be given more prominence, both to reduce biodiversity loss but also to improve the sustainability of farming systems. Selecting and adapting specific cropping systems designed to maintain or increase soil biodiversity, promoting the stabilisation of the soil environment, reducing chemical amendments, increasing biological amendments, or introducing novel technologies that optimise and reduce inputs are all potential SICS that can be utilised. This review has shown the range of SICS that can be utilised to reduce the threat of soil biodiversity loss and highlighted the research that is currently ongoing within these SICS in relation to soil biodiversity and the impact this will have on the sustainability of agricultural management.

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