SOIL ORGANISMS **97** (2) · 2025

Online First
https://doi.org/10.25674/445

# Reviving Soil Biodiversity in Agricultural Land

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Received 15 January 2025 | Accepted 5 April 2025 | Published online 23 July 2025

* This paper is part of the special collection 'Faktencheck Artenvielfalt'

## Abstract

The biodiversity of soils – from microorganisms to megafauna – supports multiple essential ecosystem services, such as food production and the regulation of soil and water quality. Climate change, land use intensification, and pollution, among other drivers, however pose a severe threat to soil organisms and can lead to the degradation of soils, especially in arable land. Hence, identifying these, often man-made, pressures and finding solutions for the sustainable management of soils can be considered one of the most important challenges of the 21st century. As part of the German Biodiversity Assessment ('Faktencheck Artenvielfalt') a group of experts summarized the available knowledge, combined with expert opinion, on the state and role of soil biodiversity in Germany. Here, we highlight past and current land use practices in agricultural ecosystems and demonstrate how various management measures affect different soil taxa. We discuss avenues of sustainable soil management, in particular different tillage regimes, organic amendments, and crop rotation, with regard to fostering soil biodiversity. We point out that any management measure must consider the local context, in particular regarding soil properties and climatic conditions, including their variability in space and time. Our results demonstrate that soil biodiversity is an integral but harmed part of arable ecosystems and summarize current and future best management practices, with a focus on Germany and comparable countries.

**Keywords** Soil management | tillage | sustainability | soil fauna | soil microbes | soil aggregation | arable land

## 1 Introduction

The decline of biodiversity and associated ecosystem services have been discussed in science for decades, including the negative consequences for humankind (Cardinale et al. 2012). At the latest since the famous study by Hallmann et al. (2017) this has been brought to public attention and widely broadcasted in the media. However, surprisingly little is known about the hidden biodiversity below our feet, although a recent publication estimated that almost 60 % of all species on earth live in soils (Anthony et al. 2023). Moreover, soils provide a wealth of ecosystem services: to just mention a few, by providing the base of plant growth, degrading dead organic matter, harmful substances and thus purifying groundwater they can be righteously considered the very base of human life, including health (Silver et al. 2021, Wall et al. 2015). Yet, worldwide soils have been degrading dramatically, or even got lost (Silver et al. 2021). In the EU alone, about 60 % of all soils are considered unhealthy (EC - European Commission 2023). In view of these facts an assessment of the soils' biodiversity appears more than urgent.

* Christian Wirth, Helge Bruelheide, Nina Farwig, Jori Maylin Marx, Josef Settele (eds.): Faktencheck Artenvielfalt. oekom verlag, 2024. (ISBN: 978-3-98726-095-7, https://doi.org/10.14512/9783987263361)


**ISSN** 1864-6417 · **eISSN** 2509-9523

Agricultural land use selects for few productive plant species, thus generally reducing biodiversity. While historical agriculture with small fields and wide crop rotations did not compromise plant succession after abandonment, the legacy of long-term intensive agriculture does not only impoverish plant communities but also negatively impacts soil properties (Cramer et al. 2008). As plant and soil communities are intensely inter-linked (Bardgett & van der Putten 2014), this will consequently cascade to the decomposer food web. For instance, a study on a long-term succession gradient (wheat field, 4-, 11- and 50-year-old fallow, beech forest), demonstrated increasingly diverse soil communities the longer agriculture had been abandoned (Scheu & Schulz 1996). A recent national synthesis, the German Biodiversity Assessment ('Faktencheck Artenvielfalt) (Wirth, Bruelheide, Farwig, Marx, et al. 2024), rendered that, out of five major habitat types covered, the largest trend of biodiversity decline was found in agricultural land (including open land). Wirth et al. (2024) also identified management measures as key factors determining if the ongoing biodiversity decline can be halted or not. Within the framework of the German Biodiversity Assessment, a group of experts revealed that, despite major advances in recent years, soil biodiversity is largely unknown, except for the larger animal groups (earthworms, isopods, spiders, centipedes, ants and ground beetles) (Eisenhauer et al. 2024). Accordingly, the effects of sustainable land management on soil biodiversity are insufficiently understood. Here, we compile selected references, including recently published meta-analyses, to focus more in-depth on management options for improving soil biodiversity in arable land. Our purpose is to illustrate past, current, and future management options in agriculturally used systems in order to halt the dramatic loss of soil biodiversity and the essential ecosystem services associated with it.

# 2 Management options

## 2.1 Soil tillage and compaction

Perhaps the most striking difference between natural and arable soils is tillage. While the horizontal and vertical structure of natural soils remains largely intact, in most arable soils it is regularly disturbed by ploughing, harrowing and cultivation – the type and extent varying between crops. Moreover, frequent use of heavy machinery compacts the soil, thus reducing the pore space which represents the habitat for soil organisms and its overall accessibility (Holland 2004, Médiène et al. 2011). Soil-protective agricultural machinery and avoiding driving on wet, in particular fine-textured, soils both have a large potential to substantially reduce this problem (Hartmann & Six 2023). Any tillage evidently affects the physical and hydraulic conditions of the soil and therefore modifies the habitat of its organisms. The effects on them vary depending on type and intensity of tillage, but also on size and microhabitat of the organisms. However, the lowest mechanical impact does not necessarily signify the greatest benefit as no tillage (NT) is generally accompanied by herbicide use. Conversely, conventional tillage with ploughing, often applied in organic farming without synthetic pesticides, cuts off roots and turns the soil upside down, which represents quite a drastic impact for soil life. Therefore, intermediate techniques such as shallow harrowing, or zone tillage (breaking only a small part of the soil between crop rows) should exert the least pressure to belowground communities. Box 1 introduces some tillage techniques and abbreviations that are referred to here.

Larger soil animals seem to be most compromised by physical soil disturbance, in particular millipeds, isopods and snails, which hardly occur in any cultivated soils (Wolters & Ekschmitt 1997). Also, Diptera – extremely diverse, abundant and important for litter breakdown – are sensitive to tillage, even more than to pesticides (Frouz 1999). Despite methodological difficulties in judging their true abundance (Mommertz et al. 1996), predacious macroarthropods such as carabids (Müller et al. 2022) and larger spiders (Sunderland & Samu 2000) become more abundant when tillage is reduced. Unlike wolf spiders hunting at the surface, the small money

**Box 1: Selected tillage techniques**

| | |
|---|---|
| P | (Mouldboard) Plough: breaking and inverting the soil to usually 15-30 cm depth |
| CST | Conservation tillage: Any type of cultivation aiming for reducing physical disturbance, in particular ploughing, often supplemented by leaving crop residues at the soil surface. CST aims for reducing both erosion and damage to soil life. |
| LP | Two-layer plow: Sophisticated plow cutting the deeper soil and plow-inverting only the upper horizon |
| CP | Chisel plow (also: cultivator, grubber): non-inverting deep tillage with longer and often broader teeth than harrow |
| H | harrow: rake-like instrument for loosening the soil surface with teeth or disks; main purpose is weed control or preparing the surface for sowing |
| LC | Layer cultivation only cuts through the soil at a given depth, keeping the sequence of horizons intact. |
| NT/MT | No / Minimum tillage: management without any or only minimal tillage; soil horizons remain intact. Weeds are removed by herbicides, occasionally also by mulching using organic residues or plastic foil |

spiders (Linyphiidae) appear less affected (Holland 2004). While endogeic earthworms may even benefit from tillage, abundance and species numbers of epigeic and anecic earthworms profit from reduced ploughing (Briones & Schmidt 2017, Holland et al. 1994, Holland 2004, Médiène et al. 2011, Pelosi et al. 2009, van Capelle et al. 2012). Rather the opposite seems to be the case for smaller fauna such as enchytraeids, springtails or mites (Hendrix et al. 1986, Nakamura & Fujita 1988, van Capelle et al. 2012). However, these results are not unequivocal: a global meta-analysis found that reduced ploughing increased the numbers of these three groups on average by 37 %, 35 % and 22 %, respectively (Betancur-Corredor et al. 2022).

At the microscopic scale, the picture becomes more heterogeneous: Nematodes are hardly affected by ploughing, yet the percentage of omnivorous or predacious species decreases in favor of bacterivorous ones and protozoans (Betancur-Corredor et al. 2022, Holland 2004, Puissant et al. 2021, J. H. Schmidt et al. 2017). Plant-parasitic nematodes were only in a poor, sandy soil increased by NT while no such effect was found by other types of CST in three other countries along a European gradient (J. H. Schmidt et al. 2017). Reduced tillage globally promotes soil microorganisms (Faust et al. 2019, Joschko et al. 2012, Kahle et al. 2010) while, depending on the context, NT may only increase fungi (Morugán-Coronado et al. 2022). Rhizosphere bacteria, saprotrophic bacteria, and fungi were more abundant in cultivated soils (CP) than in ploughed soils (Fernandez-Gnecco et al. 2022, Holland 2004). In nine German vineyards, tillage decreased microbial respiration, decomposition and fungal diversity, in favor of bacterial diversity (Pingel et al. 2023). In a 60-year study comparing tilled and no-tilled crop rotations, microbiota exhibited more stable networks and the soil C content remained stable when harvest residues were left on the ground (Liu et al. 2022).

No tillage (NT) has been advocated for many years, for erosion control and because immediate positive effects for earthworms were obvious (see above). Ulrich et al. (2010) studied a plot experiment after 37 years using these treatments: P (ploughing), chisel ploughing (CP) and NT. CP and, to a lesser extent, NT increased soil organic carbon and nitrogen content in the upper 15 cm. Earthworm numbers and biomass in CP were almost twice as high as in P and NT while the total microbial biomass declined in the sequence CP-NT-P but varied with depth: at 0-10 cm, it was highest in CP, and at 15-30 cm in P. This is corroborated by a similar study where CP and NT (compared to P) increased soil organic carbon and microbial biomass by 7 % and 20 %, respectively (Murugan et al. 2014). In that study, CP and NT fostered especially arbuscular mycorrhizal fungi. A comparison of layer cultivation (LC), P and two-layer ploughing (LP) in a plot experiment over five years revealed a clear advantage of LC for earthworms, followed by LP (Emmerling 2001). The same sequence LC – LP – P was found for microbial biomass and activity, fungi in the deeper horizon, and for aggregate stability and organic carbon (Emmerling 2007).

## 2.2 Soil cover and organic amendments

Organic substance is the very base of any decomposer food web. It enters the soil via root exudates from living plants, litterfall and, to a lesser extent, microbial primary production and animal residues such as casts, carrion, feathers or arthropod exuviae. Due to the prime role of vegetation and root exudates, carbon input is directly related to productivity. Therefore, highly productive systems such as fertilized grasslands also support a large belowground carbon input, amounting to about 60 % of the net primary productivity (Bai & Cotrufo 2022), not only ‘feeding’ the soil community but sequestering substantial amounts of carbon. Carbon sequestration is typically higher when the proportion of fungi within the microbial community increases (Six et al. 2006). Appropriate management, especially plant diversity, organic fertilization and reduced grazing, can greatly increase carbon input and sequestration, as well as converting arable fields to grassland (Bai & Cotrufo 2022, Hartmann & Six 2023). Soils rich in organic matter typically have high abundances of earthworms and predacious arthropods, which is beneficial for soil structure and helps keeping animal pests in check (Médiène et al. 2011, Sunderland & Samu 2000).

In 110 grassland plots in three regions in Germany, land use intensity had a pronounced negative effect on ant diversity, especially on *Formica* spp., mostly due to mowing and heavy cattle grazing. In turn, ant diversity was positively related to sheep grazing (Heuss et al. 2019). In the same regions no clear differences between the management types and bacterial biodiversity were found, due to large variation within two out of three management types (Nacke et al. 2011). A very high diversity of microbial species was found in an alpine grassland which had not been grazed for 60 years, alongside with very high soil carbon, nitrogen and microbial biomass (Vidal et al. 2020). In the first season of re-introduced high-intensity grazing, the microbial abundance remained constant but the community shifted towards higher abundance of bacteria. Another study along an elevation and management intensity gradient in alpine grasslands also revealed very high soil carbon at high elevation/low management intensity. The highest earthworm biomass was found at low elevation/high intensity, together with their significance for aggregate formation (Garcia-Franco et al. 2021).

A litter layer at the surface is not only a nutritious habitat but also buffers the soil underneath against climatic extremes (Fig. 1). Soil life thrives wherever there are large amounts of organic matter, i.e. in the vicinity of roots, at the soil surface or wherever dead organic matter has been transported by human activities or digging animals. Removing the largest amount of produced biomass during harvest and leaving ploughed soils bare until spring reduces the natural input of organic matter drastically, in the long-term impoverishing the soil. To prevent this, the simplest solution is intercropping, i.e. sowing other plants such as mustard or legumes directly after harvest or between plant rows (green manure). Another option is organic fertilization via farmyard manure or slurry. In the last decades, a lot of attention has been drawn to organic amendments from human activities other than farming such as mulching with compost from diverse sources or the incorporation of biochar in different preparations (Fig. 2).

A global meta-analysis revealed that bacteria, fungi and total microbial biomass all benefit from **organic fertilization** (Morugán-Coronado et al. 2022). The advantage of farmyard manure (FYM) compared to synthetic nitrogen fertilizers for soil organic matter content, microbial biomass and activity has been well documented, for instance in long-term experiments such as the 'Static Fertilization Experiment' in Bad Lauchstädt, Germany (Böhme et al. 2005). In the same site, J. Schmidt et al. (2017) studied microbe-plant interactions and microbial necromass in six different FYM and NPK mineral fertilizer treatments with or without legumes. Their presence clearly separated phospholipid fatty acid profiles of the microbiota. In sugar beet, fertilizer treatments had a stronger effect on community composition than in alfalfa, and fungal necromass was considerably higher when only mineral fertilizer was applied, compared to all other treatments. In comparison with control or straw amendment, FYM increased bacterial diversity (the effects depended on the addition of nitrogen fertilizer), but both organic amendments modified bacterial community structure (Schmid et al. 2018). The abundance of Collembola, oribatids and juvenile mites increased in fields with organic compared

**Figure 1.** Example of conservation tillage where crop residues remain on the soil. (USDA NRCS Texas – commons. wikimedia.org; CC BY 2.0)

to inorganic fertilization (Heinen et al. 2023). Among organic manure, earthworms positively react to cattle slurry and fermentation residues (Burmeister et al. 2020).

**Mulching, intercropping, green manure and wide crop rotations** all aid in reducing weeds and increase the heterogeneity of soils and thus their biodiversity. Intercropping and crop rotations significantly increased the abundance of fungi, but not bacteria or total microorganisms, as shown by a global meta-analysis (Morugán-Coronado et al. 2022). Earthworm abundance increases with a higher percentage of legumes in intercrops and with green manure (Ehrmann 1996, O. Schmidt et al. 2001, 2003; Walter & Burmeister 2022). Epigeic and anecic earthworms were 3 - 7 times higher in a 'living mulch system' with no tillage compared to both a conventional and an organic system, which both had more endogeic earthworms (Pelosi et al. 2009). Similarly, mulching and green manure increase the abundance and biodiversity of enchytraeids (Nakamura & Fujita 1988). A global meta-analysis on the effects of organic, inorganic and no nitrogen fertilization demonstrated that most studied taxa of Collembola, nematodes and earthworms were most abundant with organic N fertilization while this was not the case for mite taxa (Betancur-Corredor et al. 2023). Unlike by tillage (in three out of four sites) or fertilization, plant-parasitic nematodes were strongly influenced by crop type, with abundances of the genus *Pratylenchus* twice as high in presence of legumes compared to black oat (J. H. Schmidt et al. 2017).

In the past decades, a lot of research has dealt with **biochar**, the product of pyrolysis of different types of feedstock materials (mainly wood and crop residues, but also human and animal waste) as soil additive. On the one hand, biochar is rather recalcitrant and can thus sequester carbon in soil, on the other hand it improves the quality of many soils, especially when combined with microbial inoculants. Irrespective of feedstock, the addition of biochar to soil increases bacterial diversity, as shown in a recent meta-analysis, although the effect disappears when more than 40 t/ha are applied, or more than 300 kg N/ha (Xiang et al. 2023). The authors found the positive effect in arable land, horticulture and forests, but it was not significant in grassland. The evidence on the influence of biochar on soil animals is still scarce. Based on a literature search with a limited number of keywords, Li et al. (2024) found only 24 studies covering a range of taxa, with hardly any conclusive results, with the exception of mesofauna which appeared to benefit from biochar. The overall positive influence of biochar can be explained by a number of factors, in particular increased surface area providing higher water holding capacity, pore space for microorganisms and sorption sites for nutrients, but also for contaminants, and increased pH, which reduces disaggregation or dissolution of toxic metals. Biochar itself also serves as carbon and nutrient source, but may also contain toxic residues from the combustion process (mainly polycyclic aromatic hydrocarbons), counteracting the positive effects (Bolan et al. 2024).

## 2.3 Landscape structure and crop rotations

It is common knowledge that heterogeneity fosters biodiversity (Eisenhauer et al. 2023). This is opposed by agricultural industry focusing on productivity and efficiency: Monocultures in ever larger fields, a reduced variety of crops and their rotations, synthetic fertilizers, pesticides and other measures have drastically reduced landscape heterogeneity and biodiversity compared to pre-industrial agricultural land (Benton et al. 2003). While in a study covering 400 km, the local biodiversity of bacteria was unaffected by soybean monocultures, ß-diversity, however, was significantly lower than in


**Figure 2.** Examples of biochar application (**A**: GIZ/Tim Brunauer – commons.wikimedia.org; CC-BY-SA 4.0) or farmyard manure application (**B**: werktuigendagen – commons.wikimedia.org; CC-BY-SA 2.0).

crop rotations. Their ß-diversity was even comparable to the one of grasslands (Figuerola et al. 2015). Earthworm abundance and biomass in wheat monocultures was less than 50 % and 30 %, respectively, compared to wheat with legume intercropping which favored especially anecic and endogeic species (O. Schmidt et al. 2001). Similar results were reported from a long-term experiment in Lithuania (Bogužas et al. 2022). In another long-term experiment on potato monoculture versus crop rotation in Poland, the opposite was found for Collembola numbers. However, their species diversity was higher in the crop rotation (Twardowski et al. 2016). In 19 conventionally managed fields in Southern Sweden, introducing crop rotation led to a significant increase of Collembola, oribatids and juvenile mites, as well as of species richness of carabids and staphylinids (Heinen et al. 2023). Ostandie et al. (2021) investigated 20 pairs of vineyards under conventional and organic farming in a landscape with varying percentages of organic farming and semi-natural habitats. Considering arthropods and microorganisms (see also below), organic farming at the field scale was more predictive for their occurrence than at the landscape scale. Interestingly, except for pollinators and carabids, the proportion of semi-natural habitats in the surroundings was rather negatively related to the abundance of soil biota (Ostandie et al. 2021). Introducing crop rotation into existing eggplant monocultures increased soil organic carbon, suppressed microbial pathogens and fostered beneficial microorganisms (Ghani et al. 2022).

## 2.4 Management systems

A thorough review of any potential management systems in detail would be far beyond the scope of this study. Here we use some general principles to highlight the impact of contrasting examples on soil biodiversity and associated ecosystem services. On the one end of possible systems are any **permanent crops** such as orchards, vineyards, hop fields or asparagus. The fact that the crops including residues persist in the same area for often decades implies an ideal breeding ground for any pests, which are fought by intense use of fungicides and insecticides, often accompanied by herbicides and/or intensive tillage to reduce weeds. Eventually, this results in widespread contamination and a low overall biodiversity and biomass of soil organisms (e.g., Brühl et al. 2024, Filser et al. 1995, Pelosi et al. 2014, Phillips et al. 2024). Still, this is not uniformly the case. For instance, Decaëns et al. (2003) reported highest earthworm densities right in an orchard which, however, in their study ranged under 'medium intensity'. In vineyards, the proportion of organic farming in the surrounding area often had a contrary effect on abundances, for instance it favored pollinators, unlike the practice in the field, while for Collembola and spiders the opposite was true (Ostandie et al. 2021). In their study, microorganisms were less abundant in organic fields. Insecticide use frequency reduced pollinators, Collembola and ground beetles while fungicide use reduced Collembola and other microarthropods, in favor of mites.

Permanent cultures under conventional management must not have exclusively negative effects on soil biota. For one, the soil structure in the crop rows remains completely undisturbed for a long time. Second, highly productive crops will also assure high carbon input via root exudates, to a certain extent also by falling fruits and leaves. Third, when combined with intercrops, conservation tillage or even cattle as in the grazed orchard in the study by Decaëns et al. (2003), beneficial effects at least for some soil organisms will occur. However, as shown above, the most serious problem of permanent cultures is pesticide use.

**Conventional farming** with a more or less appropriate use of synthetic fertilizers, sometimes supplemented by manure or slurry, moderate tillage and pesticide use represents the majority of farms in industrialized countries. More concerned and informed farmers apply a range of reduced intensity systems, from integrated farming to conservation tillage (see 3.1). **Integrated farming** combines measures such as 'farming by soils' (crops and cultivars apt for the respective conditions), wider crop rotations, reducing the use of agrochemicals and minimizing soil tillage. Sometimes also the percentage of non-crop area is increased (e.g. hedges, field margins, fallow land). Tsiafouli et al. (2015) conducted a study in four European countries representing contrasting climatic conditions. Based on a wide range of studied taxa, they demonstrated the negative effect of management intensity on soil biodiversity and faunal biomass Thus, any step towards reduced management intensity can be expected to benefit soil biodiversity.

Although resulting in somewhat lower yields compared to the above systems, **organic farming** systems are beneficial for overall biodiversity, owing to usually wider crop rotations, a higher percentage of legumes and organic fertilizers and the lack of any synthetic pesticides (Mäder et al. 2002, Oehl et al. 2004). However, due to higher productivity and less tillage, conventional systems or no-till systems may also sustain a higher earthworm biomass, despite pesticide usage (Pelosi et al. 2009). This was reported by Irmler (2010) who studied earthworms on 85 sampling points over eight years during the transition from conventional to organic farming on a 176 ha farm in Northern Germany. In the first year, all fields were managed conventionally; conversion took sequentially place in the second, third and fourth year. Total abundance and biomass of earthworms declined during the study, only anecic species benefited from organic farming. The author attributed this to the large influence of rainfall, the heterogeneity of the single fields, and to the dominance of endogeic species in the conventional system. Moreover, recovery of earthworm populations after conversion may take a long time (Filser et al. 1999). This is corroborated by a follow-up study between 2005 and 2013, where the earthworm abundance and biomass slightly increased under conventional management but at least tripled in the organic or living mulch system (Pelosi et al. 2015). In the latter, mainly *Allolobophora longa* had increased while in the organic system this was the case for the three species *A. longa, L. terrestris* and *L. castaneus*. In both systems (particularly in living mulch), also *Aporrectodea caliginosa*, typical of ploughed arable land, increased more than in the conventional system. In a meta-analysis with a limited number of studies, Bengtsson et al. (2005) reported a positive effect of organic farming on the biodiversity of earthworms, microorganisms, fungi and microbial biomass or activity. Still positive but less evident was the outcome for two groups of their larger predators (carabids and spiders).

Over the last decades, the **cultivation of energy crops and agroforestry** have increasingly received attention, due to the benefits regarding raw materials and sustainable energy, and expected positive effects on biodiversity and ecosystem services such as carbon sequestration in soils. Emmerling (2014) reported positive effects of a range of perennial energy crops on abundance and biomass of earthworms. In an alley cropping experiment established in an organic and integrated farming system with *Robinia* and *Populus* trees in Southern Germany, the combination of organic farming with *Robinia* rendered the most pronounced positive effect for carbon sequestration, microbial biomass carbon and functional guilds of microbiota (Sun et al. 2018).

Management systems aiming for maintaining or increasing soil carbon increase the abundance of beneficial organisms (Liu et al. 2022), including earthworms and microorganisms that foster soil aggregation. Taken together, this improves soil structure and fertility (Filser et al. 2016, van Groenigen et al. 2019). In a global analysis on copper accumulation in vineyards and orchards, Neaman et al. (2024) showed that increased organic matter was associated with lower copper values due to surface runoff. This is an important finding as a similar process can be expected for any contaminant. Together with the fact that pesticide degradation is favored in soils with high organic matter content (Webb & Aylmore 2002) and associated biological diversity and activity, this is a strong argument for avoiding loss of organic carbon in agricultural soils. Sustainable management should strive for increasing it.

## 3 Complexity and limitations

### 3.1 Soil properties

Basic soil properties are intimately connected to the organisms living inside and affect, for instance, soil water content and infiltration, aggregation, or nutrient content. These trivial facts explain why it is often so difficult to disentangle management and soil effects on biota. Frequently soil properties such as pH, C or N content or type of crop overrule the effects of management systems (e.g., J. Schmidt et al. 2017). In a global meta-analysis on the effects of biochar on bacterial diversity, soil properties, in particular the C:N ratio, explained more variation than did biochar (Xiang et al. 2023). Soil organic carbon and clay content explained 56 % of the variation for soil aggregation in three alpine grasslands while earthworms, plants and inorganic carbon together only accounted for 23 % of the variation (Garcia-Franco et al. 2021). It is all the more remarkable that a global meta-analysis on management effects on soil microorganisms stated that the positive effects found for organic fertilization and tillage were 'not related to soil physicochemical properties and climatic factors, suggesting a positive global effect of sustainable management practices on microbial abundance' (Morugán-Coronado et al. 2022).

### 3.2 Spatial and temporal variability

Even aside soil properties, disentangling any managements effects in arable soils is a difficult task, owing to the multitude of crops and varieties, climatic and geographical conditions (e.g., Pelosi & Römbke 2016). One of the biggest challenges in soil research is their huge heterogeneity. Besides the obvious variation in climate, elevation, inclination and vegetation, soils display a high variability even at a very small scale (Filser 1996). Next to vegetation and management, the distribution of soil organisms is closely related to this heterogeneity (Fromm et al. 1993, Valckx et al. 2009). It is therefore most remarkable that the meta-analysis by Bengtsson et al. (2005) revealed very convincing evidence for soil organisms: in 44 out of 49 studies a positive effect of organic farming on biodiversity was found, in comparison to only 29 out of 42 studies for insects and four out of seven for spiders. Based on all organism groups studied (including also plants, birds, insects and pest species), the authors pointed out that the benefits of organic management were more likely to be found within intensely managed landscapes compared to more structured ones with a smaller share of arable land. Due to the low number of studies covered, this analysis was supplemented and updated later on: Tuck et al. (2014) concluded the robustness of their earlier study (on average 30 % higher overall biodiversity in organic farming) – however, this was not the case anymore for decomposers. The authors attributed this to the variation in soil type and structure, yet also climatic variation between years should be considered as soil organisms are extremely sensitive to hydrological conditions (Plum & Filser 2005).

Comparing mulched, organic and conventional management, earthworm numbers considerably varied between years: despite consistent trends, they were sometimes highest in the mulched, sometimes in the conventional system (Pelosi et al. 2009). Also, the response of microbiota to management can substantially vary with respect to climate and soil conditions, as shown for instance for the effect of farmyard manure in two long-term fertilization experiments in Eastern Germany and Hungary (Böhme et al. 2005). In a tillage experiment (Murugan et al. 2014), microbial biomass, nutrient stocks and management effects differed considerably between the four sites studied. Observations like these are rather the rule in arable field studies, especially with crop rotations which are hardly ever identical in different management systems. Yet, interactions between driving variables are not always complicating the outcome of studies but can also emphasize the relevance of studied factors. For instance, Sun et al. (2016) demonstrated that the positive effects of minimum tillage on microorganisms and associated ecosystem services were more pronounced in an organic farming system than in one with integrated farming. In a study on 150 differently managed grassland sites in Germany, Birkhofer et al. (2016) found varying effects of land use on the abundance of soil arthropods between different regions, but their feeding preferences remained constant.

One of the trickiest points in studying soil communities is the aspect of time. Many studies are short-term and often poorly replicated over time, making firm conclusions problematic. In their extensive analysis, Xiang et al. (2023) found that the effect of biochar on bacterial diversity weakened over time, disappearing after 30 months of residence time. No such effect was found for soil animals (Li et al. 2024). Despite intense

**Figure 3.** Examples of sustainable soil management via crop rotation with pollinator suitable *Phacelia* (cardephotography – stock.adobe.com).

sampling over eight years, Irmler (2010) found that rainfall explained more variation in the dominant earthworm *Aporrectodea caliginosa* than management. On the other hand, earthworm populations require a long period of time to substantially reproduce (see section 3.4): 14 years after management conversion, earthworm populations were still increasing (Pelosi et al. 2015). Yet even longer studies may suffer from legacy effects of previous management (Foster et al. 2003), as the dispersal range especially of deep-living soil organisms is limited and many soil processes take a long time to manifest.

### 3.3 Biotic interactions

For completeness, it should be briefly mentioned that the numerous biotic interactions must be considered as well, from beneficial microorganisms to viruses and pathogens, from earthworms to root herbivores and a huge variety of predators and parasites. Any positive or negative interaction partner will affect the other's fitness, thus further impeding any predictions on abundance and spatial distribution. For instance, a common finding is that invading earthworms modify the habitat of other soil organisms, in particular micro- and mesofauna, so fundamentally that not only their abundances decline but also biodiversity (Jochum et al. 2021). This modification could also explain the contrary effects of crop rotations and monocultures on earthworms and Collembola described in section 3.3. Within one group, each species occupies its special niche, as shown, for instance, for anecic earthworms. *Allolobophora longa* preferred areas with high electrical conductivity while *Lumbricus terrestris* preferred the other end of the scale (Valckx et al. 2009). Accordingly, the distribution of these two species along a distance gradient from a river differed as well (Decaëns et al. 2003). Similarly, along an elevation and intensity gradient in alpine grasslands, two epigeic earthworm species, *L. castaneus* and *L. rubellus*, showed opposite preferences along the gradient (Garcia-Franco et al. 2021). In grasslands worldwide, the effect of grazing on carbon input depends not only on soil properties and climate but also on the vegetation, other herbivores, grazer species and grazing intensity (Bai & Cotrufo 2022).

## 4 Conclusions and outlook

Evidently, due to the context dependency of the measures covered here, there is no standard recipe for improving soil biodiversity. Still, our study identified a number of measures that can be implemented in agriculture for the sake of soil biodiversity, e.g., crop rotations with plants that also support aboveground biodiversity (Fig. 3). Most of their positive effects have been known for a very long time. All the more shocking is the fact that apparently no lessons have been learnt – otherwise we wouldn't face such a dramatic decline of not only soil, but overall biodiversity, mainly due to agricultural intensification and pollution (Phillips et al. 2024, Wirth, Bruelheide, Farwig, Settele, et al. 2024). Irrespective of management system, clearly more species exist in semi-natural and natural areas (Jeanneret et al. 2021). To prevent further loss of biodiversity and to retain the multiple functions performed by soil organisms (Wagg et al. 2014) it is important to not further increase the area of arable land. We hope that our compilation contributes to further improve farming practice and, more important, agricultural policy (Pe'er et al. 2020, Wirth, Bruelheide, Farwig, Settele, et al. 2024).

## Acknowledgements

We acknowledge funding by the German Federal Ministry of Education and Research within the Research Initiative for the Conservation of Biodiversity (FedA) under the funding code 16LC2001B and by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG; FZT 118, 202548816; Ei 862/29-1).

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