

## Chapter 18

# Soil health and biodiversity: Interactions with physical processes and functions

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## Introduction

### Risks and threats on soils as multifunctional reactors

Soils, as a three-phase system, are the most vulnerable constituents on earth, because they are not renewable. At the same time, they provide us not only food, feed, and fiber but also clean ground water and sufficient drinking water. But soils are also essential as a living medium for microbes up to macrofauna. Soil properties, like soil strength, total porosity, pore continuity, pore-size distribution, and air capacity, and soil functions, like plant-available-water storage and nutrient storage due to cation-exchange processes, all impact plant growth, root development, and the depth distribution of roots. Furthermore, these properties and functions affect total biomass production, activity of soil biota, and the type and amount of soil carbon (SOC) and vice versa. Thus, soils are multifunctional reactors.

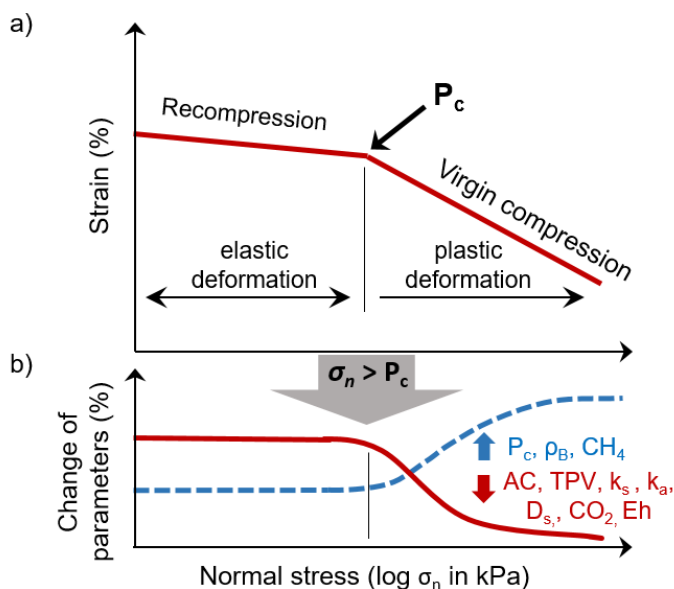
The functions are, however, threatened by soil acidification, erosion by wind and water, or soil deformation due to soil compaction and shearing, which do not only result in changes in the proportions of air, water, and solid volumes, but also in their spatial arrangements and pore continuity. Furthermore, such modifications cause changes in soil structure, pore connectivity, and particle or pore surface accessibility. They depend on water saturation and physicochemical reactions. The role of the biodiversity pool in all these multifunctional interactions is, however, often neglected, although bioturbation, exudates, and physicochemical reactions are interlinked with the functional community structure of soil organisms and their individual abundances. The organic input of vegetation and the dynamics of root growth affect these interactions. Haas et al. (2018) described the complex reactions and interactions at the root surface within the rhizosphere and also documented the consequences on physical, chemical, and physico-chemical reactions. However, these interactions are even more complex. The dramatic loss of biodiversity in time and space is known (IPBES, 2019), including the fact that one million of the estimated 8 million species of animals, plants, and fungi on earth are threatened with extinction rates at least 10 times higher than in the last 10 million years. The corresponding adaptation of land-use and soil-management practices for sustainable agriculture and soil protection is still insufficient to overcome the loss. A recent report (Leopoldina, 2020) states that, for Germany and Central Europe, many species, plants, and soil inhabitants are increasingly being reduced as a result of the intensification of land use. Such intensification includes many interlinked processes, which cause not only direct changes in the processes but also alter many more soil properties and functions.

Soil resilience, therefore, only defines a quasi-dynamic equilibrium. Impacts beyond the internal soil rigidity, caused by thermal, mechanical, hydraulic, or chemical processes, alter the equilibrium conditions until a new steady state is reached. The consequences of such impacts due to either natural soil processes, like acidification and clay migration, or anthropogenic processes, like degradation due to sealing, erosion, or soil deformation, all affect this quasi-dynamic and, therefore, sensitive equilibrium. The equilibrium is finally affected by the worldwide changes of the climate.

## Soil biodiversity perspectives from soil physics

### Soil compaction and shearing deform the environment of soil biota

Each mechanical stress applied to soils can be attenuated without any change in soil functions, if the internal soil strength, defined as the precompression stress, is not exceeded down to a certain depth (Horn, 2021) (*Figure 2a*). In case of its exceedance, however, these properties will be changed until a new equilibrium is reached (*Figure 2b*).



**Figure 2.** Stress-strain relation and the consequences for elastic (recompression line) or plastic (virgin compression line) soil behavior **a)** as well as for relative changes of soil properties. **b)** The precompression stress ( $P_c$ ) defines the internal soil strength and the resilience limit. During the recompression load range, the properties and functions remain mostly unchanged while in the virgin compression load range the application of increasing stresses induce changes in the following:  $P_c$ ,  $\rho_B$  = bulk density,  $CH_4$  = methane emission,  $AC$  = air capacity,  $TPV$  = total pore volume,  $k_s$  = saturated hydraulic conductivity,  $k_a$  = air conductivity,  $D_s$  = gas diffusion,  $CO_2$  = carbon dioxide emission,  $Eh$  = redox potential.

If divergent particle movements are caused by cyclic loading events, both air and water as 2 components of the 3-phase system must be also considered because stress induced drainage of air coincides with matric potential changes from negative to positive pore water pressure conditions. The loading events also coincide with weakening and altered swelling and are followed by shrinkage processes and with the formation of new and less rigid structure conditions or increased pore tortuosity with consequences for many soil processes (Zhai and Horn, 2018, Huang et al. 2021a). These interactions are furthermore enhanced if stress application includes shearing, because stress-induced strain does not only affect soil properties and functions through the aggregate breakage or particle rearrangement, but it also includes an interlinked change in pore water pressure. These dynamic processes result in an additional worsening of the pore tortuosity and reduced hydraulic flux and even retarded gas fluxes and a prolonged water

saturation with further impacts on physicochemical processes, like a declining redox reaction followed by altered mobility of Fe, or Mn (Horn, 2021; Huang et al. 2021b). The alteration of the activity of the microbial community, and even the change of the soil from a sink to a source for greenhouse gases like methane ( $\text{CH}_4$ ), can be detected as a consequence of soil deformation. The alteration is related to the (micro-)structural soil stability and the deformation behavior of soils (Haas et al. 2016).

Divergent and shear processes are, therefore, the main driving forces for changes in soil biodiversity. They impact the community structure of soil organisms and their activity. Keller et al. (2019) documented the long-term, tillage-dependent yield loss, as well as the impacts of heavy machinery on root growth. They also observed increased densification of the plowpan layer and its enlargement with depth. As a consequence, Horn et al. (2019) documented a more enhanced horizontal anisotropy of the saturated hydraulic conductivity in arable subsoils of a model region (Schleswig Holstein, Northern Germany). Corresponding alterations in water and gas fluxes between the top- and subsoil will certainly affect the biological activity and abundance of soil microorganisms with consequences for the whole soil biodiversity pool.

## **Bioturbation – burrowing soil animals as drivers of soil development**

Soils differ in terms of their biodiversity. From a global perspective, climate is a determining factor (Phillips et al. 2020), but also other factors, such as parent material, relief, water, vegetation, and human activities are important. For example, it is well known that soil properties such as pH and soil carbon control earthworm occurrence and diversity. Most earthworm species prefer soils with neutral to slightly acidic pH values. Soil organisms are significantly involved in different soil processes, e. g. decomposition and transformation of organic matter and litter, new formation of humic substances, or structure formation and bioturbation.

Bioturbation has already been described by Darwin (1881). Intense bioturbation is only observed in soils with favorable water, air, and nutrient conditions. Burrowing soil animals mix the litter layer with the upper mineral soil and produce a humic (=h) topsoil (A-horizon) with a characteristic crumbly structure. Bioturbation also promotes infiltration, even in compacted layers (e. g. Ruiz et al. 2015) and prevents other soil processes (e.g., decalcification), because soil animal activities can move translocated substances back to the surface again or transport subsoil material and deposit it on or in the topsoil (Blume et al. 2016). They can even change the morphology of the soil significantly (e. g. termite hills, Kristensen et al. 2015). In some black humus-rich soils like Chernozems (IUSS Working Group WRB 2014), bioturbation due to earthworms (worm-bioturbated=Vermic) and steppe mammals (hamsters, etc.) is so dominant that an A-horizon of more than 1 m can develop. Some of the topsoil material can reach very deep in animal burrows that have been filled with organic material (crotoovina). Those black humus-rich soils are typically distributed in continental long-grass steppe regions, because the animals burrow deeper to avoid dryness in summer due to heat and in winter due to frost.

*Table 1* illustrates the soil fauna activity (bioturbation) of the macrofauna in different landscapes. Bioturbation depends, obviously, on soil and climatic conditions. Earthworms, termites (which are particularly numerous in Africa and America), and ants (which can nearly be found all over the world) are known as ecosystem engineers, which change the physical structure of soils due to bioturbation, and even small mammals like moles and voles dig through the soil. In fact, the highest bioturbation is reached by lugworms on flat tidal coasts (Tidalic Gleysols,

IUSS Working Group WRB, 2014), where the upper 15-25 cm of the topsoil is constantly mixed during low tide.

Animals	Ecotope	Animals
Earthworms	Meadows (UK) <sup>a</sup>	18-45
Earthworms	Gardens (Centr. Europe)	10-25
Earthworms	Meadows (Centr. Europe)	5-120
Earthworms	Forests (USA)	18
Earthworms	Tropics	36-270
Ants	Forests, steppes (Europe)	31
Ants	Steppes	31
Ants	Ants moist area (USA)	20
Ground squirrels, susliks	Steppes (Russia)	18
Ground squirrels, susliks	Semi-deserts	1.5
Prairie dogs	Prairies	70
Moles	Forests (Europe)	7-120
Termites	Savanna	12-60
Termites	Deserts	0.02-5
Lugworms	Mud flats (Europe)	600-3000

<sup>a</sup> after Darwin (1881)

**Table 1.** Bioturbation (in Mg ha<sup>-1</sup> y<sup>-1</sup>) in different soils around the world (Blume et al. 2016)

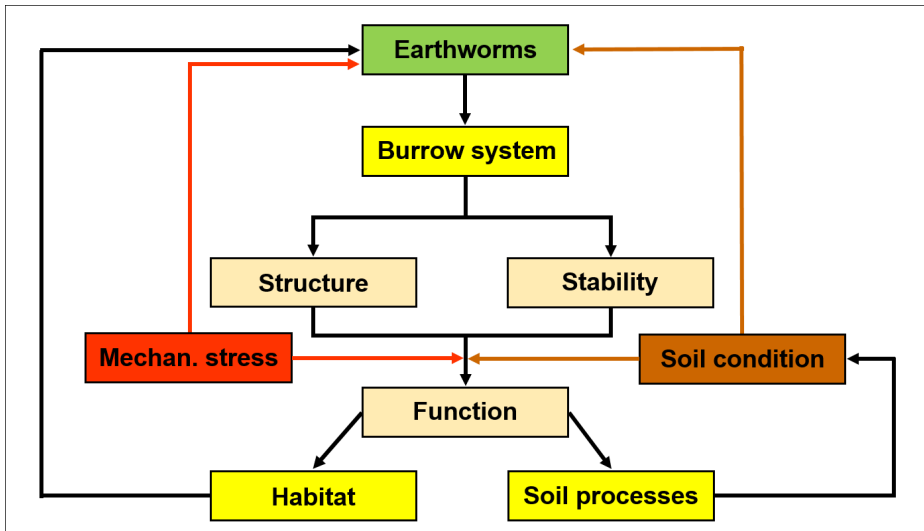
In this context, interactions within the soil biodiversity pool and with its abiotic environment provide ecosystem services that shape or stabilize the soil system and that are used by humans in agricultural management. Amongst others, we can define the following ecosystem services:

- regulation of the biogeochemical cycles
- storage and supply of nutrients for plant growth
- formation, strengthening, maintenance, and renewal of the soil structure
- breakdown of waste or pollutants
- control of the hydrological cycle
- regulation of atmospheric trace gases
- regulation of soil-borne plant diseases
- function as a genetic reservoir for further usage options (e.g., in biotechnology)

Thus, the structural and functional diversity of soil organisms is an essential prerequisite for the functioning of terrestrial ecosystems as a whole and of agro-ecosystems (for further details see also Fonte et al. 2010).

## Earthworms as ecosystem engineers

Within the soil biota pool, earthworms are multiple actors (according to Turbé et al. 2010) as (1) biological regulators of microbial communities (2) chemical engineers as decomposers of organic residues, and (3) ecosystem engineers modifying their environment physically by shaping the soil structure. Their role as ecosystem engineers covers the formation of aggregates (clay-humus-complexes) and macropores (burrow systems). *Figure 3* demonstrates burrow formation and functioning, which are in conflict with mechanical stresses and soil conditions. In arable land (here with focus on physical conditions), the earthworms' activity for burrow formation is affected by the given local soil conditions and the intensity of mechanical measures. The resulting burrow system with its structure and stability is affected by both factors, which control the functions of the burrow system as a habitat for the earthworms, other soil biota, and roots. The burrows also control other soil processes, such as infiltration, transport of soluble compounds, aeration, reduction of runoff, and erosion. These burrow-controlled processes, in turn, shape the soil conditions.



**Figure 3.** Soil as living space for earthworms under land use, which are in conflict with mechanical stresses and soil conditions.

## Soil biota and alterations due to soil deformation

The activity of soil organisms concentrates in “hotspots” of functional domains of the soil system, such as the detritosphere, rhizosphere, drilosphere, and porosphere (Beare et al. 1995). Although these hotspots only cover less than 10% of the soil volume, they are characterized by much higher process rates compared to the average soil conditions (Beare et al. 1995; Kuzyakov and Blagodatskaya, 2015). Thus, the availability and accessibility of organic substrates inside such hotspots like intact aggregates or in the whole soil profile, determine the microbial activity, because micro- and macro-organisms, as potential decomposers, require adequate environmental conditions, such as oxygen, water, and energy supply (Doran and Linn, 1984; Six et al. 1998; King

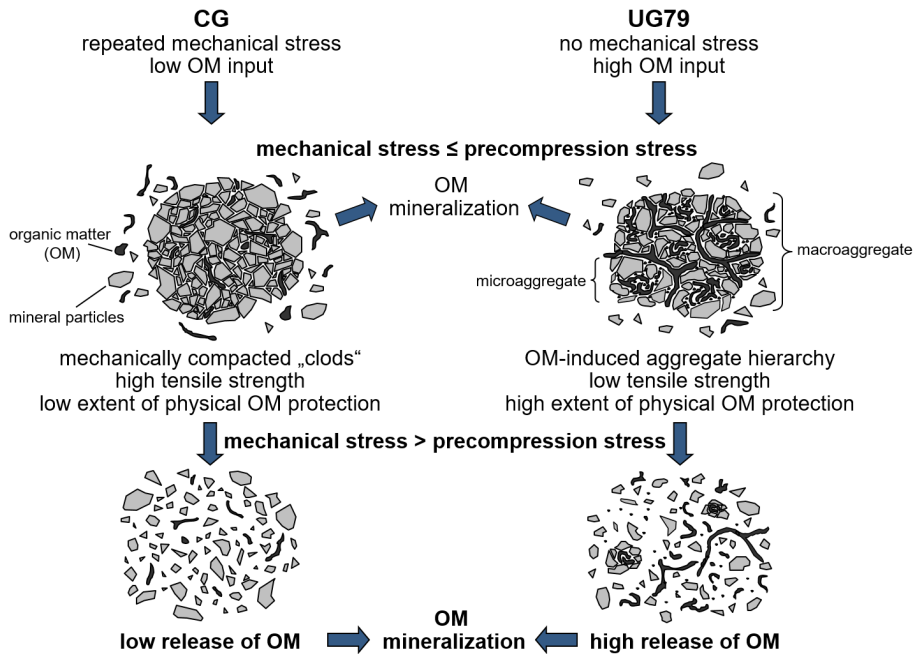
et al. 2019, Young and Ritz, 2000, Nawaz et al. 2019). If external mechanical stresses threaten these hotspots, changes in the soil-organism communities, and their composition therein, will occur because shearing interrupts the soil-pore continuity and connectivity resulting in isolated pores. In this situation, the oxygen level declines rapidly and modifies microbial communities, which results in a shift from aerobic to mainly anoxic processes with consequences for the cycling of nutrients (Stepniewski et al. 2002).

Consequently, physical soil parameters, like pore size distribution and matric potential, become crucial in understanding carbon-turnover processes and biological activity (variations in  $\text{CO}_2$  efflux), and the variation in the belowground microbial and faunal community structure, at given locations within the soil matrix (Killham et al. 1993, Mordhorst et al. 2014, Althoff et al. 2009). Kochiieru et al. (2018) emphasized the influence of macroporosity, surface area, and macropore range on  $\text{CO}_2$ -efflux and its strong relationship to soil type and land use as a documentation of microbial activity and composition. Jasinska et al. (2006), Wiesmeier et al. (2012), and Carlesso et al. (2019) stated a strong link between the microbial activity and soil strength, carbon storage, and mechanical impacts. The relationships also underline the link between the mechanical hydraulic-pneumatic, thermal, and physicochemical processes and functions (for more details see also Richards et al. 1997, Horn, 2021).

The impact of compaction on changes in microbial community structure and activity is highly variable across different soil textures, compaction levels, and water contents (Santrucková et al. 1993, Ruser et al. 2006, Frey et al. 2009, Pengthamkeerati et al. 2011, Carlesso et al. 2019). However, compaction-induced changes in the pore system leads to less favorable conditions for microorganisms, which is mainly attributed to restriction of gas or water fluxes and lower aeration status due to reduced porosity (Whalley et al. 1995, Otten et al. 2000, Beylich et al. 2010), refinement of pore sizes and disconnection of transport pathways by soil compaction (Doran and Linn, 1984, Pengthamkeerati et al. 2011).

In laboratory experiments, Mordhorst et al. (2014) showed that structural deterioration by mechanical loading exceeding internal soil strength led to a strong reduction in basal respiration ( $\text{CO}_2$ -efflux). They also gave a positive outlook, because the inhibition in soil respiration was not persistent, if the soil was exposed thereafter to natural structure formation processes, induced by wetting and drying, which re-improve the micro-environmental soil conditions of the habitat pore space. Furthermore, they stated that, if through structure deterioration by shear and compaction the accessibility of particle surfaces and coinciding biological impacts are increased, we can expect a coinciding reduction in organic soil carbon due to a complete release of  $\text{CO}_2$  to the atmosphere (Wiesmeier et al. 2012) (*Figure 4*). This latter effect is, however, negative for global-change aspects and for the requested increase in carbon as contribution to the 4/mille initiative (Chenu et al. 2019). Thus, the rigidity, quantified as precompression stress, separates the beneficial storage and increased accessibility from the non-rigid conditions. This is followed by a complete alteration of the physicochemical properties and processes that affect the internal soil processes and the atmospheric composition.

In the medium term, microbial activity is likely to increase again after an enhanced energy supply (e.g., occluded carbon inside of aggregates) followed by structural rearrangements caused by mechanical and hydraulic stresses. This implies a high susceptibility of physical protection mechanisms for carbon and a high biological activity due to the mechanical disruption of the soil structure.



**Figure 4.** Effects of soil strength on pore rigidity and carbon as well as climate change (taken from Wiesmeier et al. 2012). CG = continuously grazed site, UG79 = ungrazed site since 1979

Besides the often-described indirect impacts, mechanical stress by soil compaction affects soil biota also directly. Heisler and Kaiser (1995) reported a decline in collembolan densities and changes in their community structure due to an increasing wheeling frequency on arable land. In relation to a modified pore size distribution, the size-class of soil fauna communities seems to play an important role. Numbers of earthworms and enchytraeids decrease generally, irrespective of the species diversity and the functional groups they characterize (Röhrig et al. 1998, Langmaack, 1999). Similarly, collembolan abundances decrease with increasing compaction; however, a few species remain unaffected or even increase in numbers (Dittmer and Schrader, 2000). Soil compaction does not change the numbers of mites, in general, but modifies their community structure with both a decrease and an increase of the abundance of different species (Schrader and Bayer, 2000). Finally, nematodes, as members of the soil microfauna, do not change in numbers, but they respond with a functional change in their community structure (Bouwman and Arts, 2000). Results from a field experiment in a grassland with increasing compaction by wheeling with 4.5 Mg, 8.5 Mg, and 14.5 Mg loads, compared to the uncompacted control, revealed a significant shift towards a nematode population with increased numbers of herbivores and decreased numbers of bacterivores and omnivores or predators (Bouwman and Arts, 2000). This functional change has important implications for the soil food web and the incidence of plant diseases by phytopathogenic nematodes (herbivores) feeding on living roots.

Three years after soil compaction by six times wheeling with 5 Mg, earthworm and enchytraeid populations recovered along with a recovery of soil physical parameters, like bulk density, air capacity, and air permeability in the topsoil (Langmaack, 1999, Langmaack et al.

1999a). Recovery of earthworm populations results in expanding burrow systems as a newly formed macropore network and increasing amounts of casts as newly formed aggregates. Such reformed aggregates are, however, less stable compared to compacted aggregates of the bulk soil. They have about 10% higher porosity, which promotes water and nutrient storage processes (Larink et al. 2001). Furthermore, these porous aggregates offer space as a habitat for soil microorganisms. Earthworms reorganize soil structure; however, they do not loosen a compacted soil profile (Sauzet et al. 2021).

## Interaction between soil strength and pressures exerted by earthworms

Precompression stress defines the internal soil strength as the combined result of natural soil structure formation due to swelling and shrinkage, its intensity and frequency, chemical processes, and biological activities.

Thus, when earthworms modify their soil environment by ingesting and egesting soil, as well as by pushing soil as consequence of their peristaltic locomotion, they need to apply forces, which affect the surrounding soil in axial and radial directions forming the so-called drilosphere analog to the rhizosphere. Soil displacement declines with distance from the earthworm individual (Barnett et al. 2009), which results in a spatial gradient with decreasing bulk density towards the soil matrix (Schrader et al. 2007). Generally, radial pressures are higher than axial pressures (Table 2), which is the same relation as for root growth. Growth pressures of roots, for example of pea seedlings (*Pisum sativum*), are ca. four times higher compared to earthworm pressures (Misra et al. 1986). However, growth pressure declines rapidly with age of roots when hydraulic growth is replaced by cell division. Endogeic earthworm species exert the highest radial pressures, whereas anecic species exert the highest axial pressures (Table 2).

Functional group	Species	Axial (kPa)	Radial (kPa)
Anecic	<i>Aporrectodea longa</i>	115.77	177.00
	<i>Lumbricus terrestris</i>	90.60	136.26
Endogeic	<i>Allolobophora chlorotica</i>	65.43	78.66
	<i>Aporrectodea caliginosa</i>	68.95	294.57
	<i>Aporrectodea rosea</i>	70.11	182.43
	<i>Octolasion cyaneum</i>	63.49	183.91
Epigeic	<i>Dendrobaena octaedra</i>	43.10	81.82
	<i>Lumbricus rubellus</i>	50.43	126.02

**Table 2.** Maximum axial and radial pressures (kPa) of common earthworm species during burrowing activity with respect to their ecological classification of anecics (deep burrowers), endogeics (topsoil burrowers), and epigeics (shallow burrowers); data from Keudel and Schrader (1999).

Thus, the more the number of earthworms is reduced due to tillage or intense mechanical stress with compaction and shear effects, the less intense is the new formation of earthworm channels as highly connected macropores. Bioturbation and soil mass movements are also reduced. The vertical channels especially improve the mechanical soil strength, because these

pores are already equilibrated with the major vertical stresses and maintain their functionalities (Zhai and Horn 2018, 2019), and serves as food for microorganisms.

Roughly estimated, the earthworm species *L. terrestris* mechanically affects a soil volume of  $126 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$  in arable soil profiles of Luvisols, based on field data of earthworm populations and computed tomographic recordings of burrow systems in soil columns (Schrader et al. 2007). An annual production of burrow length of  $82.3 \text{ km ha}^{-1}$  has been calculated for *L. terrestris* populations in arable land under conventional management without compaction and only  $3.3 \text{ km ha}^{-1}$  after compaction by six times wheeling with a load of 5 Mg (Langmaack et al. 1999b).

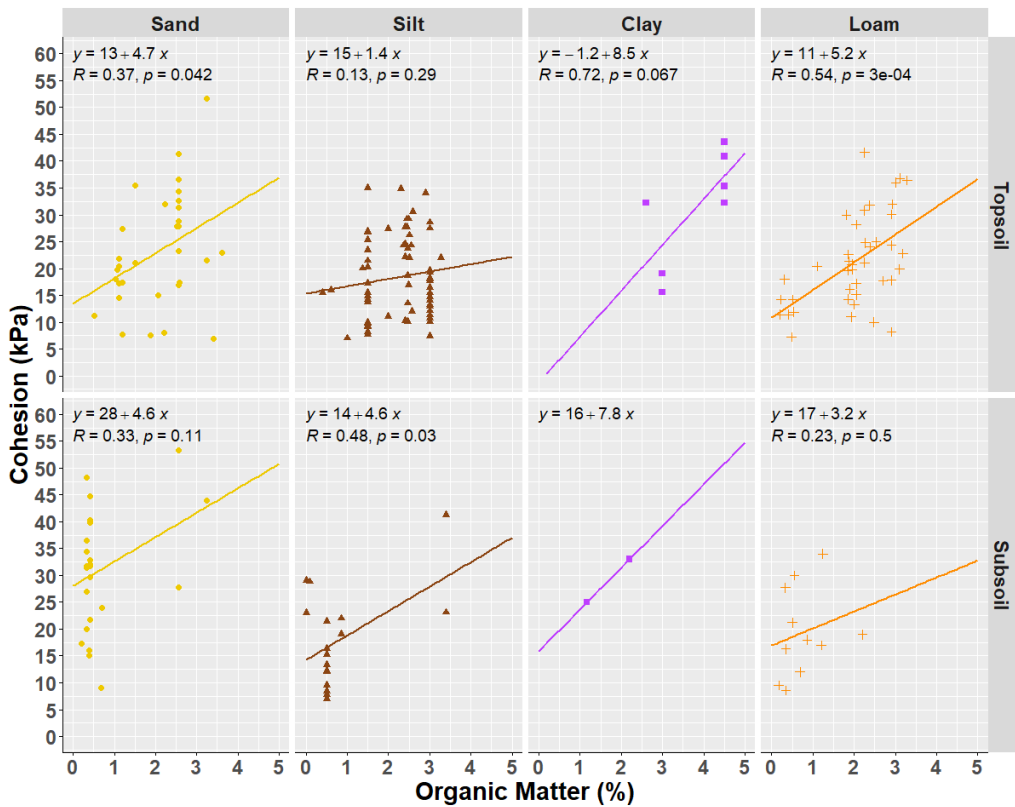
Mechanical stress by wheeling affects soil bioturbation of earthworm communities differently, depending on the tillage system. In a three-year field study on a Luvisol, soil bioturbation was always higher under conservation tillage (CS) than conventional tillage (CT) (Schrader and Larink, 2003). In the first year, in uncompacted plots, cast production was highest ( $37.8 \text{ Mg cast dry weight ha}^{-1} \text{ y}^{-1}$ ) under CS, which was nearly twice as much as under CT ( $18.6 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ). As a result of six times wheeling with 5 Mg, cast production under CS decreased to  $25.0 \text{ Mg ha}^{-1} \text{ y}^{-1}$  and under CT to  $5.7 \text{ Mg ha}^{-1} \text{ y}^{-1}$  (Schrader and Larink, 2003). Two years later, under CT, soil bioturbation in the compacted treatment was still ca. 50% below the uncompacted treatment, whereas under CS soil bioturbation was on the same level in both treatments (Schrader and Larink, 2003). Thus, under consideration of the actual internal soil strength with respect to mechanical impacts and optimal climatic, soil moisture, and plant growth rate conditions, a long-term recovery of the soil biodiversity pool and its functionality can be expected. In different forest types of cold-temperate regions, an average soil bioturbation by earthworm communities of  $25 \text{ Mg dry weight ha}^{-1} \text{ y}^{-1}$  has been calculated (Taylor et al. 2019). But the effects of mechanical stress on community structure and frequency of microorganisms and the long-term recovery of soil functions are unknown (Riggert et al. 2019).

## Interdisciplinary perspectives from Agronomy

### Land management impacts on carbon storage for soil biota and consequences for soil properties and functions

It is well known that most soil properties, such as soil structure and hydraulic properties, as well as the diversity and activity of soil organisms, are influenced by the quantity and quality of soil organic matter (SOM, which contains about 58 % SOC). It is also a key attribute of environmental quality and agronomic sustainability (Carter, 2002) and serves as food for microorganisms. It is essential for chemical, physical, and mechanical processes in soils at all scales. SOM leads to a more stable, habitable pore space and increases soil aggregation, and, hence, the ability of soils to withstand shearing forces, resulting in a more stable, habitable pore system.

These statements are derived from data collected over the last 40 years. Increasing the content of SOM enhances the mechanical strength, defined as cohesion (kPa), for the different soil texture classes according to Ad-Hoc-AG Boden (2005). It is also known that these relationships furthermore differ based on soil structure (Figure 5) (Schroeder et al. 2021).

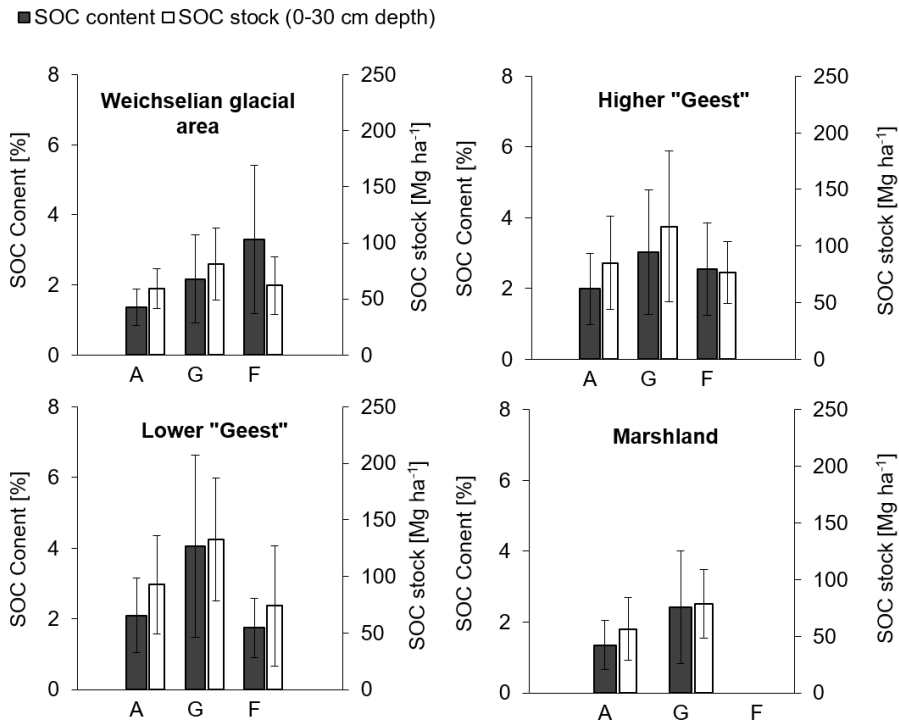


**Figure 5.** Changes in soil cohesion (kPa) with soil organic matter (%) divided into topsoil (n=139), subsoil (n=52), and the main texture classes of arable sites with  $\text{CaCO}_3 < 1\%$ , at a pre-drainage of -6 kPa, n = 191.

Besides the well-known organo-mineral bonding effects, the impacts of microorganisms enhance soil strength, which also explains the reduced rigidity of soils with a smaller contents of SOM.

Therefore, structural elements, like soil aggregates, plant roots, or preferential flow paths, can be expected to increase the biodiversity in soils, because the physical transition zone, in terms of the oxygen partial pressure across the coated walls of earthworm burrows (Haas et al. 2018), is known to be highly biodiverse. Additionally, instead of the expected increase in SOC according to the 4/mille predictions (Chenu et al. 2019), investigations on soil carbon stocks (down to 90 cm depth) documented the impact of land use (arable land, grassland, and forest) for 925 soil profiles in 4 different geological regions in Northern Germany (Mordhorst et al. 2018). Highest carbon stocks in the 0-30 cm depth were found in soils under grassland use, and the lowest were found under arable use (Figure 6).

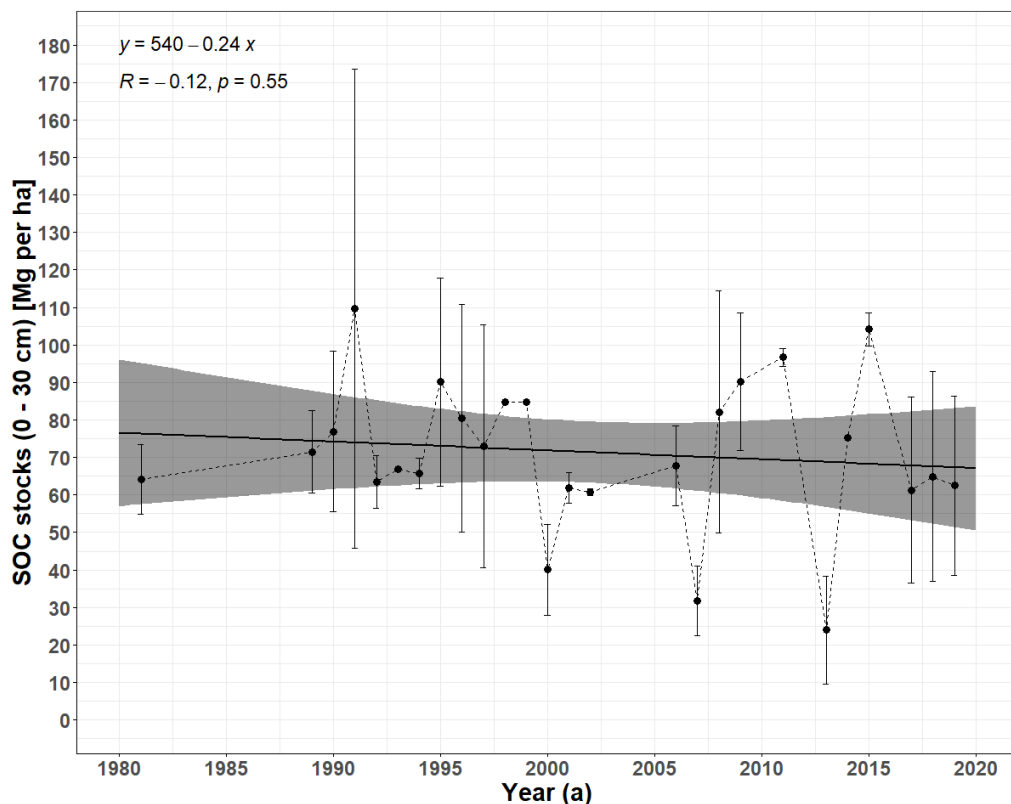
Similar studies also stated that the high spatial variability in SOC content in top- and subsoils relates to the combination of soil type, climate, and topography, as well as the actual and historical land use (Wiesmeier et al. 2012, Mayer et al. 2019).



**Figure 6.** Effect of land use management (A = Arable land, G = Grassland, F = Forest) on mean soil organic carbon (SOC) content of mineral A-horizons and SOC stock within 0–30 cm depths for the region-specific soil types in Schleswig-Holstein (Northern Germany). Organic soils are excluded. Published in Mordhorst et al. (2018).

How far these processes can actually explain the 40-year trend in declining SOC content in arable soils in Germany (*Figure 7*), in combination with the increasing mechanical impacts (Keller et al. 2019), is often brushed aside. But the increasing irreversible soil degradation worldwide should strengthen our activities to prevent such impacts. The link between the decline in organic carbon with time and the increasing soil degradation due to soil deformation affects biological diversity and will end in a reduced functionality of soils, which are non-renewable. Feedback mechanisms react at all scales, because a reduced SOC content in soils coincides with a reduced internal soil strength, increased soil surface sealing, and increased surface runoff and water erosion, which, in combination, reduce nutrient and water storage (Wiesmeier et al. 2020).

Decline in storage of plant-available water and nutrients affects biological activity and community structure. Overall, soil properties and functions, including the total amount, the composition, and distribution of the organic substrates, and biological activity are directly linked and are strongly dependent on anthropogenic impacts. Thus, in conclusion, the need to fulfill the Sustainable Development Goals (SDGs) gains high importance.



**Figure 7.** Average soil organic carbon stocks (SOC in  $\text{Mg ha}^{-1}$ ) in arable topsoils at an assumed thickness of 30 cm between 1981–2019,  $n = 245$ .

## Impacts of soil biota for economic approaches – some remarks

Because the ecosystem services of soil organisms in agro-ecosystems help to secure yields, they are also of economic value. The activities of earthworms, in their multiple functional roles (Turbé et al. 2010) as ecosystem engineers, chemical engineers, and biological regulators, can be assigned to indirect economic values (Decaëns et al. 2006). It is difficult to quantify the value in concrete terms. Nevertheless, a recent study has succeeded in assigning an economic value to earthworm services by calculating the standard gross margin (SGM) as a measure of the relative contribution of crop production to overall farm revenue (Plaas et al. 2019). While Plaas et al. (2019) used fungicide applications and their potential for reduction due to feeding of earthworms on phytopathogenic fungi, Jonsson et al. (2019) based their concept of an economic analysis on fertilizer applications. Schon and Dominati (2020) defined a set of proxies to develop a monetary valuation of earthworm services in different pastoral systems. These ecological-economic approaches open up the possibility of evaluating the performance of soil biota depending on soil conditions and management measures, taking them into account in the context of recommendations for sustainable management measures. Contrary to some

examples of chemical impact, an ecological-economic assessment of mechanical impact is still lacking. Valuation of soil ecosystem services delivered by the soil biodiversity pool provides perspectives for assessing the sustainability of agricultural management measures with respect to, for instance, reaching the Sustainable Development Goals (SDGs) of the UN and the Green Deal targets of the EU; for the soil perspective of SDGs see Keesstra et al. (2016) and of the Green Deal see Montanarella and Panagos (2021).

## Conclusions

Soil properties and functions are affected by natural pedogenic and anthropogenic impacts, which result in a site and management specific soil resilience due to the various sensitivity of soil horizons.

Exceeding the internal soil strength changes physical, chemical, and biological functions, including structure and activities of the biodiversity pool.

Earthworms can withstand external stresses applied, and, as well, they themselves can actively reform coarse pores and improve the pore continuity and mechanical properties over depth; they also can affect the accessibility of particle and pore wall surfaces for hydraulic, thermal, and pneumatic processes, as well as chemical or physico-chemical reactions.

Impacts of land management on carbon storage must be considered as a key issue, because carbon directly impacts soil biota with consequences on soil properties and functions.

Evaluation of soil ecosystem services delivered by the soil biodiversity pool provides perspectives for assessing the sustainability of agricultural management measures with respect to, for instance, reaching the Sustainable Development Goals (SDGs) of the UN and the Green Deal targets of the EU.

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## **SUSTAINABLE SOIL MANAGEMENT AS A KEY TO PRESERVE SOIL BIODIVERSITY AND STOP ITS DEGRADATION**



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