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Scoping Document

Outlook on the knowledge gaps to improve soil structure

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1. Introduction

Soil is healthy when it is in good chemical, biological and physical condition and can continuously provide as many ecosystem services (such as safe, nutritious and sufficient food, biomass, clean water, nutrients cycling, carbon storage and a habitat for biodiversity) as possible (European Environment Agency 2023). Soil structure contributes to all soil functions that underpin ecosystem services (Fig. 1). Water regulation, purification, and habitat provision are crucial for maintaining nutrient cycling, as well as disease and pest suppression, which in turn support soil productivity and its role in climate regulation (Schulte et al. 2014). Therefore, disturbances to natural soil structure impact ecosystem functioning. However, the relative importance of these different ecosystem services provided by soil structure in different pedoclimatic zones, soil types and land-use types may vary. Also, the info on the importance of protecting soil structure and on the best management practices needs to reach the diverse group of relevant actors from land owners to decision makers.

Soil structure really makes soil what it is and is vital for functioning of soil. Soil can exhibit a single-grained structure in which separate mineral particles are not aggregated but are only loosely packed like in sand dunes. Soils can also exhibit massive structural condition in which separate soil particles are bound together by cohesive forces. Massive structure can be found deep in soil profiles in a fine textured soil. However, in most soils, there is some type of aggregation where mineral particles are forming clusters as a result of drying and wetting cycles, chemical ponding and biological activity. The aggregate structure promotes soil health by allowing water infiltration, aeration, root growth, and nutrient cycling as well as by providing niches for various soil organisms. In organic soils, that are formed through the accumulation of partially decomposed plant biomass in fens and bogs, the structure is defined by the peatland vegetation and the degree of the decomposition (Rezanezhad et al. 2016).

A beneficial soil structure (left) supports multiple soil functions that underpin essential ecosystem services for human society, including:

1. Water infiltration
2. Water retention
3. Water purification
4. Water provision
5. Habitat provision for soil organisms and
6. Plant roots
7. Carbon sequestration, and
8. Evapotranspiration

Soil with poor structure (right) is prone to:

1. Surface runoff as infiltration is hindered by compaction and poor surface structure
2. Water not percolating through the soil profile will not get purified resulting in e.g. nutrient losses
3. The capacity of soil to store water and
4. Provide habitat for soil organisms and plant roots is diminished, resulting in poor plant growth and therefore
5. Reduced carbon sequestration

Figure 1. doi

A beneficial soil structure (left) supports multiple soil functions that underpin essential ecosystem services for human society. The problems that are occurring within the EU and globally are illustrated on the right-hand side.

Soil structure has been defined as the “spatial arrangement of solids and pores at scales smaller than the soil horizon and consists of clusters of solids and pores called aggregates, that have hierarchical, emergent properties, and memory that define their functions” (Yudina and Kuzyakov 2023). Some of the pores should also be continuous and large enough enable preferential flows and rapid infiltration. The arrangement of the particles, aggregates, and voids determine the capacity of soil to transmit solutes (water and nutrients) and gases (oxygen, carbon dioxode, methane, hydrogen) through the soil volume, and to retain and provide water substances such as nutrients to plants and soil biota. Important is also the significance of aggregate size variation in soil formation and its relationship with microbial communities and soil functionality like water and gas flows for rooting. See vocabulary for soil structure in Table 1.

Table 1.

Vocabulary related to soil structure

Term	**Explanation**
Water retention	Soil's ability to store water. With a smaller suction (<100 kPa) the amount of water retained depends mainly on the capillary effect and pro-size distrubution, with larger suctions mainly on the soil texture and specific surface of the soil
SOM	Soil organic matter, soil solids that consists of plant or animal tissue in various stages decomposition
Soil structure	Spatial arrangement of solids (clay, silt and sand sized particles) and pores in a volume of soil
Pore space	Volume of the space between the solid particles in the soil
Pore size	Size of a pore described usually by the diameter
Pore space	Continuity of pores (% of total porosity V/V) - essential for saturated hydraulic conductivity to ensure infiltration under flooded conditions
Wilting point	The minimum amount of water in the soil that the plant requires not to wilt. Below the wilting point, water is held so tightly in the soil matrix that it cannot be taken by the plants
Field capacity	The amount of water retained in the soil after excess water has drained due to gravity
Particle size distribution	Shares of different sized particles in a mass of soil
Bulk density	Measure of the mass of soil in a given volume, often expressed in grams per cubic centimerer (g/cm^3)
Macro pores	Macropores are large soil pores, typically Ø greater than 30μm, which allow for the rapid movement of water and air through the soi. (incl. pore shape - look above)
Micropores	Small soil pores, typically Ø smaller than 30μm, water moves mainly by diffusion and by plant uptake
Organic soil	Soil formed through the accumulation of partially decomposed organic biomass (Metsämaa-Forest soils Glossary 2024)
Mineral soil	Inorganic soil, loose inorganic matter formed from the bedrock as a result of geological processes
Growth factor	Any internal or external element that influences the growth, development, or reproduction of a plant

Good soil structure helps to resist soil erosion and compaction, which can degrade soil quality (Rabot et al. 2018) (Fig. 1). Thus, the structural quality of soils can be defined according to their resilience to climatic disturbances, such as varying weather conditions, field traffic/forest machinery and/or management practices such as tillage. European Environment Agency (2023) has listed soil processes than can potentially weaken the soil status. Soil compaction and erosion are indicated as important processes that weaken soil quality, and they are tightly linked to soil structure. While human interventions like artificial drainage can enhance biomass production in wet conditions, practices such as intensive tillage and the use of heavy machinery can destroy soil aggregate structure and cause compaction, compromising the soil's ability to store and purify water. A good soil structure is an optimal balance between water retention and hydraulic conductivity and to gas exchange in soil.

Soil erosion and elemental leaching, as well as resilience to drought periods, are linked to soil structure determining e.g. soil moisture conditions (Luk 1985, Dorman et al. 2015, Wei et al. 2007). Knowledge of the soil structure is in key role when estimating soils' ability to store and conduct water as well as their water infiltration capacity (Burger and Kelting 1999, Schoenholtz et al. 2000Drobnik et al. 2018). Water retention is responsible for life on Earth as we know it. It allows for a huge air-water interface which permits aquatic aerobic activity to proceed under a range of environmental conditions.

Soil structure and related moisture conditions control biogeochemical processes essential e.g. to timber (Henttonen et al. 2014) and food productivity. Optimal soil structure supports primary production through water retention and habitat provision for biota that contributes to nutrient cycling, and pest and disease control.

2. State-of-the-Art

2.1. Current state of the knowledge on Soil Structure

Soil structure dictates the hydraulic properties of soil and is dependent on the soil properties such as organic matter content, texture including claye minerals or stones, and compactness of the particle arrangements. Bulk density is often seen as a indicator of the soil structure, but it is texture depended and does not indicate the pore size distribution (Wösten et al. 2001, Van Looy et al. 2017, Launiainen et al. 2022). Water retention characteristics (WRC) and hydraulic conductivity can be determined by direct in-situ or laboratory measurements or estimated using pedo-transfer functions (PTFs) based on the soil data (Wösten et al. 2001, Van Looy et al. 2017). Important parameters to be measured for soils from the point of view of soil hydraulic properties are e.g. total porosity (TP) and the water content of the soil at field capacity (FC) which is the amount of water stored in soil against drainage (Cools and Vos 2020, Launiainen et al. 2022). For plant available water, the wilting point (WP) is a crucial parameter especially in dry conditions (Cools and Vos 2020, Launiainen et al. 2022). The available water capacity (AWC) is the plant available water between FC and WP (Launiainen et al. 2022). Knowledge about these parameters forms a basis for estimating the effect of soil structure on soil hydrological conditions.

In many cases there are knowledge gaps in data on water retention characteristics (WRC) of soils (Launiainen et al. 2022). According to Launiainen et al. (Launiainen et al. (2022) hydrological, biogeochemical and forest models require data on WRC to perform improved hydrological predictions for forest soils. Similarly, understanding a soil's susceptibility to compaction and to characterize soil mechanical properties as a function of soil moisture requires more data of the compressive behavior of the different soil types in different moisture conditions (Torres et al. 2024).

Fig. 2

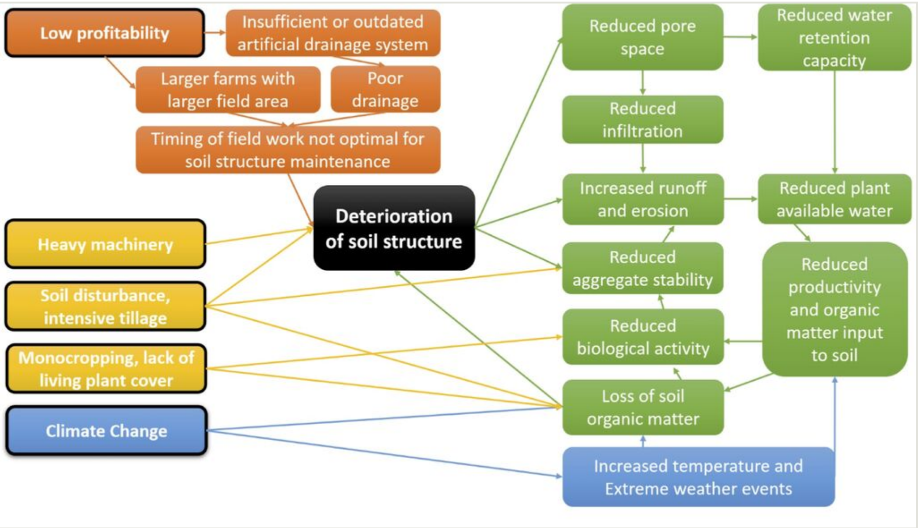

Figure 2. doi

Drivers (black borders) affecting structure of agricultural soils include factors such as overall policies and economic situation (orange), soil management practices (yellow), and environmental factors (blue). Structural deterioration can impair soil functioning and create a vicious cycle of further soil weakening

Intensification of land management, especially soil tillage,is a key driver of soil structural deterioration (Keller et al. 2019, Klöffel et al. 2024). Increasing weight of the machinery used in agriculture and in forestry poses a threat to soil pore system through compaction causing changes in pore volume, pore-size distribution, and connectivity. In addition, heavy machinery can compact deep soil layers and then recovery can take longer than compaction in surface layers (Berisso et al. 2012). From a biological perspective, the pore network is highly pertinent as it is the habitable space for microbial species and compaction affects directly to the habitat of soil biota (Longepierre et al. 2021). Report of the Finnish Ministry of Environment (Haavisto 2023) indicated also that soil compaction was one of the most important processes that can weaken soil status. However, in

Finland, while there are individual scientific studies on soil compaction in agricultural, forest, and urban soils, large-scale monitoring at the mapping level is lacking. This means that there are knowledge gaps in soil compaction information at nation-wide level (Haavisto 2023). This is probably the case also in many other countries.

Mechanisation of agriculture has enabled intensive tillage which is related to reduced aggregate stability and increased risk for surface sealing and erosion (Bronick and Lal 2005). These management-induced changes in soil pore system affect water and gas movement in soil (e.g. Strömgren et al. 2016) and therefore, also the living environment of soil biota and plant roots (Oades 1993). When changes in aggregate stability and pore system lead to reduced soil productivity, soil biodiversity, the input of carbon (C) through decaying plant materials as well as exudates and debris of soil biota (Costa et al. 2018) as well as soil necromass is also reduced leading to decreasing organic carbon (OC) content in soil. Lower SOC content is related to lower aggregate stability (Six et al. 2000, Soinne et al. 2016) thus enhancing further the risk for structural deterioration.

The growing interest on reduced tillage and carbon farming have potential to improve aggregate structure but improving the growth conditions of roots and enabling proper water and gas movement deeper in the soil would require loosening the soil structure at least down to the desired root penetration depth. No-till management known to improve soil aggregate stability may, depending on climate and soi type, enhance soil compaction and therefore slowly lead to lower productivity. On the other hand, reduced disturbance of soil improves the living conditions of soil organisms and therefore may have positive effect on soil porosity and macroporosity.

Similarly, as in agriculture, forest management practices (timber extraction, land preparation by terraces, and so on) affect soil structural properties. Different management practices also bring along forest floor vegetation changes mediating the effects of drought on soil. One example are the forest fires in Portugal which are a major threat affecting soil structure, soil biota, soil physicochemical properties with also off-site effects (flooding, ash deposition in damns, etc.).

In addition to soil management, climate change puts the soil structure on stress through extreme weather conditions. Extreme rain events lead also to changes in pore structure which maintains the healthy soil. Drought can cause irreversible or reversible shrinkage of soil leading to preferential flow paths for water solutions. Drought has also been shown to decrease carbon accumulation to soils and the forest stand age and management can affect the resilience and response of soil to drought and heat waves. We do not know what happens to soil structure when these extreme weather events follow each other repeatedly. There should be critical analysis of some emergency measures currently adopted in the post-forest fire phase, such as emergency stabilization or aerial seeding. The advancing climate change can lead to continuous change in soil structure, and we need more information on ecosystems that undergo change such as thawing permafrost.

While we can destroy soil structure with, for example intensive and wrongly-timed soil tillage and forest management practices and excessive handling of soil (Fig. 2), we can also preserve soil structure. Regenerative agriculture practices (e.g holistic grazing, catch crop, cover crop and crop rotation among others) provide an option for the intensive management practices. But can we improve/regenerate destroyed structure of arable mineral soil? Or will the structure and functioning of restored peat soil be equivalent to the unmanaged peat areas?

2.2 Prioritization of knowledge gaps

Methodology

The methodology used followed the SOLO Think Thank methods and is described in Fig. 3. We started with desk research by Think Thank leaders and members and continued with stakeholders through multiple approaches. Priorisation of the 10 key knowledge gaps took place in an online meeting with stakeholders and scientist and in Bulgaria by key stakeholders. Voting was conducted in Bulgaria, online and for soil structure Think Tank we organized a separate voting during the Finnish Soil Sciences days. Each stakeholder could vote for the three most important knowledge gap or request some of them to be combined. Intriguingly, in the online meeting and during the Soil Sciences days, the same top three were formed.

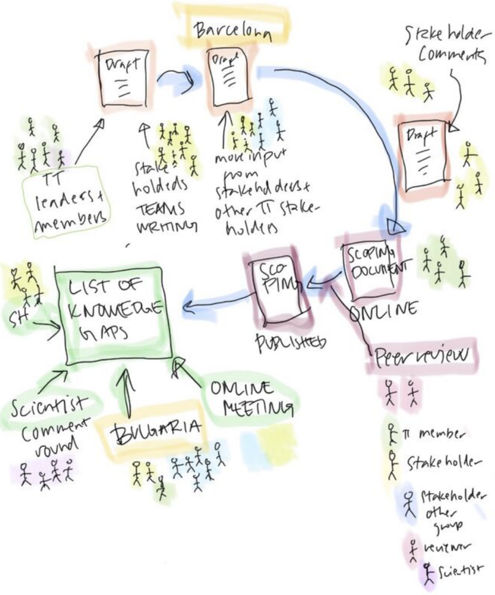

Figure 3. doi

Methodology of soil structure Think Tank.

A list of the top 10 identified knowledge gaps can be found in Table 2:

Table 2.

Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is given in section 3.3)

Rank	Knowledge gap	Type of knowledge gap
1	How can we manage and adapt soil structure to support effective water regulation and habitat provision across scales - from microhabitats to catchment areas - in the face of climate change and evolving lang-use practices?	Knowledge development gap, Knowledge application gap
2	How can we quantify and value soil structure to support sustainable land management, economic assessments, and predictive modeling across scales and applications?	Knowledge development gap
3	How do biological, physical, and chemical factors in soil interact to build and maintain its structure, and how can management practices harness these interactions to enhance soil structural resilience or restore it after deterioration?	Knowlegde development gap, Knowledge application gap
4	How do forest management (timber extraction, soil preparation) and other disturbances (forest fires) effect soil structure and what are the off-site effects (e.g. flooding)?	Knowledge development gap
5	Impact of circular economy and soil improvement materials in maintaining or improving soil structure in changing environment	Knowledge development gap
6	How is a changing climate and operational/business environment challenging current management practices, and what impact will it have on soil structure if these practices are maintained or adjusted to the changing environment?	Knowledge development gap, Knowledge application gap
7	How can we increase the interest towards soil structure and knowledge on the role of soil structure (especially sub soil) on water management among the lang-managers? How can we help farmers and land managers to avoid management-induced soil structure?	Knowledge application gap
8	How compacted is the soil, and can the soil recover from compaction? Soil sealing and the effect on soil structure, can the soil recover from sealing?	Knowledge development gap
9	Supply chain pressure: How do we get better contracts for the farmers so that the contracts don't put them in field at the wrong time?	Knowledge application gap
10	Does soil classification based on soil texture lose the information needed for soil structure management?	Knowledge development gap

3. Roadmap for Soil Structure

3.1 Key knowledge gaps

1. How can we manage and adapt soil structure to support effective water regulation and habitat provision across scales—from microhabitats to catchment areas—in the face of climate change and evolving land-use practices?

The change in management or caused by natural disturbances may lead to new structural state in soil or the change may be short-lived and there will be a reversion to the pre-disturbance state. The consequences of these changes in land management or changes resulting from natural disturbances, and the rates of these changes may differ depending on climate, soil type and vegetation cover, management, and disturbance history. For example, the use of heavy machinery may lead to soil compaction affecting soil functions like water flow, regulation and retention, soil aeration, habitat provision and therefore ability of soil to provide ecosystem services such as primary production. Compaction and reduced plant growth can lead to increased runoff of nutrients and carbon, and reduced drought tolerance. Compaction may cause problems for soil organisms and their function (Meurer et al. 2020) decreasing their biological activity and leading to lower decomposition of soil organic matter and disturbing the maintenance of soil structure due to reduction of exopolysaccharides, glomalin and fungal hyphae. Therefore, more information is needed on specific management practices in different climatic environments and soil types that consider the land-use and functioning of the soil for provision of as many as possible ecosystem services.

Changing intensity of weather events resulting from climate change can cause problematic soil structural changes that need to be examined more. With changes in weather events and in annual timing of them, there is a transition in timing of the soil management practices at both forest soils, agricultural soils and in the urban areas. When the soil is too moist, certain machinery cannot be used without causing dramatic effects to the soil structure. Proper winter in Northern Europe with frost period protects soils from damage and allows use of heavy machinery (e.g. in forests). In addition, frost and freeze-thaw cycles are reported to improve soil structure in arable lands by fragmenting large soil clods and therefore enhancing consolidation of beneficial seedbed (Leuther and Schlüter 2021). However, the reported effects of multiple freeze-thaw cycles on aggregate stability vary, with studies reporting both increased and decreased aggregate stability (Lehrsch 1998, Kværnø and Øygarden 2006, LI and FAN 2014, Wang et al. 2012). Unfortunately, currently climate change appears as milder temperature and increased precipitation in winter period, leading to greater moisture content and leaching of mineral and organic material from the soils (greater erosion) (Kværnø and Øygarden 2006). In addition, the possibility for increased leaching is not restricted only to mineral and organic matter but may concern also particulate material (suspended solids) as well as nutrients essential for e.g. forest ecosystems in the long run (Machado et al. 2018). Increased occurrence of heavy rain is possible also in more Southern regions, and thereby the concern of the loss of soil organic matter and soil structural changes is global.

Abnormal weather events make trees susceptible to forest diseases, and in turn, loss of trees alters soil stability. The impact of extreme weather events on soil structure can vary by soil type, potentially leading to either improvement or degradation. It is essential to develop management strategies that account for both extreme rainfall and extreme drought. This could include novel thinking in crop rotations and plant breeding to enhance possibilities for green plant cover throughout the year.

Soil operations affect the soil structure, but with optimal timing the destabilising effect can be reduced. For example, soil wetness and inherent soil properties contribute to soil structural vulnerability and their interaction is complicated depending also on the management practices (Hu et al. 2023). Also grazing and compaction by animals can be severe (Pietola et al. 2005). Minimum tillage has been considered the best approach from numerous biological points of views such as symbiotic fungi and arthropods, although this might not necessarily be the case with increasing number of weeds and reduction in yield levels. Furthermore, omitting tillage have been reported to result in enrichment of nutrients like phosphorus in the uppermost surface layer (Jarvie et al. 2017 , Uusitalo et al. 2018). This will lead to increased risk of loss of dissolved phosphorus into surface water increasing eutrophication (Jarvie et al. 2017, Uusitalo et al. 2018). Additionally, if soil water management like drainage is not functioning properly in clay soils, the aggregates loose stability under water saturated conditions. Therefore, we need information on soil specific management options in different climatic conditions and land-use systems to improve the functionality of soil structure.

On forest land there is a growing interest among landowners towards continuous cover forestry, where one avoids clear-cuts, or site preparations for the planted trees are targeted for one seedling separately to avoid overall soil tillage. If continuous cover forestry practices get more common in organic soils where it is more applicable than in mineral soils, and this may result in a significant change by reducing the need for soil preparation and for maintenance ditches on drained peatlands. Different harvesting practices may also have a variable effect on the forest soil structure and nutrient amounts remaining in the site after cuttings. If cutting includes all tree compartments (whole tree harvesting), this increases the loss of organic matter and nutrients compared to that remaining in the soil in stem-only harvesting. The distribution of logging residue piles on the site may also affect soil structure (physical properties) and nutrition (organic matter, chemical properties), i.e. if the logging residues are located only on restricted parts in the harvested area due to modern harvesting techniques. In addition to physical soil management, human induced land use also includes change in plant species, particularly in agriculture but to certain extent also in forest systems. The narrowing of plant species selection has further extended to genetic diversity via the use of breeding of plant material often to maximize productivity. Plant breeding has changed root exudates, root microbes, soil chemistry via microbes, lack of arbuscular mycorrhiza, glomalins and other extracellular polymeric substances (EPS) thus affecting the soil structure.

The emerging issue of microplastics in European soils is conceptually also a physical contaminant and affects soil aggregation and pore-size distribution (Han et al. 2024, Wang et al. 2023). However, the impact is likely to fluctuate based on the textural composition of the soil, as well as the size, shape, and aging characteristics of the microplastics particles (Lehmann et al. 2021,Wang et al. 2022).

The improvement of soil structural quality resulting from changes in soil management can be assessed by physical-structural-hydrological parameters (aggregate stability, MWD, pF-curves, bulk density, Ksat values) and methods linked to soil microbiology. A particular challenge is that, in many cases, soil in poor condition is not very responsive to management practices.

2. How can we quantify and value soil structure to support sustainable land management, economic assessments, and predictive modeling across scales and applications?

Good soil structure is characterised by an arrangement of particles that facilitates the movement of water and air, while also providing stability to resist erosion and compaction. However, soil pore space (total pore volume and pore size distribution) varies greatly depending on soil particle size distribution and thus, the optimal structure or pore-size distribution that can be obtained or maintained varies depending on soil type. Also, land-use and location of the soil sets different expectations for soil structural functioning. In a cool humid climate, it is essential to get the excess water drained from the fields in the spring to get the growing season started whereas in the catchment scale, it is important to maintain areas that can hold the draining water to level of the flood peaks. Therefore, the evaluation of the goodness of soil structure should be done considering the ecosystem services that are expected the soil to produce within the land-use and the capacity of the specific soil type.

Soil aggregates are considered for hot spots for biological activity and biogeochemical processes and are of high importance defining soil structure and pore space. However, the efficacy of aggregate research in elucidating functioning of soil structure has come under scrutiny. Sampling aggregates has required disrupting the surrounding soil environment, raising concerns that aggregates may partially result from the sampling procedure, thus potentially compromising their representativeness (Young et al. 2001, Garland et al. 2023). Furthermore, non-destructive imaging techniques have failed to detect aggregates in undisturbed soils or in deeper soil layers (Garland et al. 2023). Recently, Garland et al. (2023) concluded that aggregates can be separate units but taking into account the processes contributing to the formation and turnover of aggregates, they do not need to have distinct physical boundaries. In fact, tillage-produced aggregates are often loosely packed and form inter-fragment spaces whereas natural aggregates are more likely to be seamlessly embedded in the surrounding soil matrix (Or et al. 2021). Yudina and Kuzyakov (2023) stated that they “consider the pores and the interfaces as the arena of the physico-chemical and biological processes, but aggregates as the result of these processes“. Consequently, aggregates are the core concept of stable pedogenic features (soil memory) and allow the realization of a thermodynamic view on the soil structure. This further highlights the importance of understanding aggregation and developing methods to study aggregates in their functional surrounding.

How to measure soil structural functioning at relevant scales? Assessing the soil structure holds a great variety of analysis methods. Soil compaction can be for example estimated by determining precompression stress, penetration resistance, soil organic matter as well as hydraulic conductivity and plant available water capacity (European Environment Agency 2023). Different methods emphasize different aspects of soil structure, and some may be suitable for only certain kind of soils. Some methods are cheap and widely applicable in context with the field sampling and utilised for example in the current European-wide field studies and surveys, but less informative and difficult to be interpreted. For example, soil bulk density (BD) is widely measured property used to describe soil structure. However, interpreting BD results from soils with various mineral composition of particle size distribution is difficult. Furthermore, BD is a static measure lacking the link to soil functioning and information for example on pore connectivity. On the other hand, certain newer methods, such as X-ray computed tomography (CT), allows visualization and quantitative analysis of the interior of porous structures (Haubitz et al. 1988) and provide in depth information e.g. on soil pore connectivity through quantitative image analysis tools (Koestel 2017), but are expensive and need rare equipment.

Further, soil structure contributes to ecosystem services in different scales (micron, pedon, catchment), and upscaling the information from small sized samples (Ø 5 – 10 cm) is challenging taking into account the large heterogeneity of soil structure in space (Vereecken et al. 2019). On the other hand, collection of large number of samples would not be feasible. So far, a satisfactory way to measure soil structure non-invasively and at relevant field scales has not been available (Romero-Ruiz et al. 2018). Therefore, effort is needed to make best out of new and rapidly developing technologies (e.g., satellite data, AI, digitalization, imaging, etc.) to combine soil structure related measurements at different levels. Combination of new technologies such as nanoscale geophysics, tomography, spectrometry, or single cell genomics (Hartmann and Six 2022, Romero-Ruiz et al. 2018) to Sentinel or other satellite derived data are probably needed to bridge the still existing knowledge gaps between soil management and structural features such as pore structure, connectivity, and soil functioning. Furthermore, it is crucial to develop methods for continuous measurements that capture the short-term changes in soil when not at equilibrium state (in contrast to current laboratory measurements).

Soil structural characteristics are currently not properly accounted in global hydrological and climatic models largely due to the methodological constrains (Launiainen et al. 2022, Vereecken et al. 2022), although recent efforts in model development have been promising (Jarvis et al. 2024). Efforts put on developing methods for measuring functioning of soil structure in different scales support the large scale hydrological and hydromechanical modeling (Fatichi et al. 2020). Better hydrological models will help to estimate the impact of structural quality on soil functioning and in ecosystem service provision considering the changes in agricultural management and climate in the future (Jarvis et al. 2024). This can help in estimating the economic value of the properly functioning soil structure and therefore provide motivation and resources to enhance soil structure improvements.

3. How do biological, physical, and chemical factors in soil interact to build and maintain its structure, and how can management practices harness these interactions to enhance soil structural resilience or restore it after deterioration?

Soil microorganisms play a key role in the formation of soil structure and its dynamics. In addition to bacteria and soil microfauna, particularly fungi are shown to be involved in the formation and stabilization of soil aggregates, also at the macroaggregate scale (Lehmann et al. 2020). Soil aggregating capability of fungi is hypothesized to be due to their physical, morphological, chemical and biotic traits. Fungal diversity in soils is high, and also large differences among fungal species are found in their ability to aggregate soil (Lehmann et al. 2020). Furthermore, recent experiments indicate that by fungal inoculation, soil hydraulic properties and aggregation can be improved by connecting soil particles via hyphae and modifying soil aggregate sorptivity (Angulo et al. 2024). The effect varied according to the fungal strains and soil moisture levels.

Soil aggregate stability is often used as an indicator of soil structure (Six et al. 2000) and reflects soil's ability to stand erosive forces. Soil aggregates are associates of organo-mineral particles bound together with forces that are stronger than the forces between adjacent soil aggregates; biologically synthesised extracellular polymeric substances (EPS). EPS are composed mainly of polysaccharides, proteins and DNA excreted by soil microorganisms. EPS are also responsible for the cohesion of microorganisms and adhesion of biofilms to surfaces, they affect soil spatial organization and enable interactions among microorganisms (Costa et al. 2018). The cementing agents that enhance aggregate formation are well-known and natural aggregates are formed as a result of biological activity resulting in stabilization by biopolymers, and mineral particle enmeshing by hyphae and roots. Small and fine roots produce optimal conditions to form and to stabilise aggregates due to the polysaccharides produced by the microorganisms (Hallett et al. 2022). Furthermore, the roots maintain separation between the aggregates.

In agriculture, tillage produces soil fragments similar to biologically formed aggregates, but the stability of the fragments against mechanical disturbance and wetting is lower (Or et al. 2021). More information is needed on how these differently formed aggregates impact the functioning of arable and natural soils and on the relative importance of these different types of aggregates in preserving soil organic carbon stocks in different soil types and under different land-use and management. Small-sized aggregates seem to improve soil hydrological properties like water retention capacity and infiltration, so the estimation of this fraction or derived indexes or ratios, which relate the percentage of micro to macroaggregates, can give an interesting information about the condition and degradation of Mediterranean soils.

The fundamentally important interactions between chemical and biological factors in maintenance of soil structure provide a clear potential introducing new possibilities for soil management, also in the context of climate change. We agree that the first step is to identify the most important key organisms supporting soil structure. However, rather than direct cultivation, understanding the ecology of the key microorganisms would provide more efficient long-lasting impact. Supporting ecosystem of the key organisms, such as suitable carbon support via host plant or interacting helper microbes would be way to soil structure improvements via use of soil biota.

Indeed, biological processes influencing soil structure are not happening only microbial but rather in plant root-microbe interphase. Roots and attached microbiota improve nutrient cycling, stabilization of soil against erosion, water balance of soils and even soil carbon storages (Hallett et al. 2022) as well as may mitigate soil compaction damages (Jin et al. 2017). Abundant use of fertilizers decrease the benefit of root–soil interface in nutrient uptake, and modern crop cultivars may have smaller root systems. These may lead to lowered amount of rhizodeposition and eventually impact on soil properties. Plant breeding is suggested to be a potential future tool in harnessing the root-soil interphase to build and preserve soil structure and sustainability (Hallett et al. 2022). Another interesting suggestion is that, as ethylene has been found to act as an early warning signal for roots to avoid compacted soils, this could provide a pathway for how breeders might select crops resilient to soil compaction Pandey et al. (2021).

We need information, not just on agricultural soils, but on the physico-chemical processes, all the biological processes and interactions, from larger plants and animals to fungal hyphae and tiny microbes. How soil organisms interact with each other and with the abiotic environment affects soil structure. The role of soil invertebrates in crop production has received relatively little attention. The biotic part maintains the structure, how is it affected by climate change and changes in the soil habitat? How do soil animals and microbes respond to extreme events?

Recovery of soil after disturbances is tightly linked to soil structure. We do not know how long it takes for soil to recover nor how we should measure soil recovery. The anthropogenic effects have a major role in shaping soil structure, but we do not have a complete and soil- and climate-specific understanding on their direct impacts on soil structure and how to retain sustainability of soil after disturbance. The potentially important role of plants in restoration needs also more soil and management specific understanding. Furthermore, as the functioning of soil results from an interplay of soil structure and activity of soil organisms, recovery of the vast areas of deteriorated soils on earth is a challenge.

3.2 Prioritized knowledge gaps

4. How does forest management (timber extraction, soil preparation) and other disturbances (forest fires) affect soil structure and what are the off-site effects (e.g. flooding)?

Timber extraction is performed in forests nowadays often using machinery which may cause in some cases soil compaction. After clearcut, it is typical to perform soil preparation in order to improve soil structure and properties for tree growth of the next tree generation. There is a need for more information on how soil preparation actions affect soil structure in a long run (e.g. SOC development, mineral weathering) and nutrient leaching. Forest fires impact soil organic matter, clay mineral structure, and can significantly alter the soil pore system (Agbeshie et al. 2022), thereby affecting overall soil functioning. Therefore, the risk and frequency of forest fire occurrence should be assessed, and their potential impacts on soil functioning carefully evaluated.

5. Impact of circular economy and soil improvement materials in maintaining or improving soil structure in changing environment

Agricultural use of organic amendments derived from the pulp and paper industry have generally shown positive impacts on soil physical properties such as soil aggregation. Sludge addition has also reduced particle and phosphorus losses from soil to percolation water, indicating potential for erosion mitigation (Rasa et al. 2020). However, when enhancing circular economy, the quality of the materials in question should be carefully investigated in the light of soil functioning since side streams may contain harmful substances that impair for example soil structure stability and functioning. Therefore, more information is needed on the impacts of different side streams on soil structure in different soil types and climate conditions.

6. How is a changing climate and operational/business environment challenging current management practices, and what impact will it have on soil structure if these practices are maintained or adjusted to the changing environment?

Poor profitability of agriculture may impair the investments needed for adjusting production to maintain soil structure in changing climate. Furthermore, changing diets change the crop rotations and quality of organic matter input into the soil. Also new crops may require new type of machinery which should be evaluated in the light of changing climate.

7. How to increase the interest towards soil structure and knowledge on the role of soil structure (especially sub soil) on water management among the land-managers?

Among farmers, nutrient inputs have gained a lot of attention, and this may originate from the fertiliser industry being a large business. However, soil structure is as important growth factor as poor structure may significantly prevent the plants from utilizing the nutrient input given in fertilisers. Therefore, knowledge on soil structure and how to manage the structure of different soil types is crucial information to improve or maintain soil productivity as well as to reduce environmental impacts of food production.

8. How much the soil has compacted and can the soil recover from compaction? Soil sealing and the effect on soil structure, can the soil recover from sealing?

Plant roots are able to modify soil structure via numerous mechanisms, for example pore formation (Jin et al. 2017). Thus, when aiming to recover soils after compaction, in addition to management, increase in root growth may improve plant resource accessibility, and thereby also crop productivity. Increased root growth has also long-term effects on compacted soil via organic matter feed. The root penetrability and growth could be improved through plant breeding (Colombi and Keller 2019, Hallett et al. 2022). In forest soils, the key issue is in avoiding compaction by operational planning of forest management, such as which forest units to be cut in which season and which machine resources to be used (Labelle et al. 2022). Operations eg. usage of mulch to accelerate the recovery of soil properties, or even mechanical site preparation, could be used for loosening the topsoil.

9. Supply chain pressure: How to get better contracts for the farmers so that the contracts don't put you in the field at the wrong time?

Farmers' contracts with traders can be very binding and require delivery of products at the exact time agreed. However, the ripening of the harvest and the farming practices are highly dependent on weather conditions. Excessively tight contracts can force farmers to harvest under conditions where soil strength is too low, for example, due to excessive wetness. In this case, adherence to the contract will lead to a deterioration of the soil structure and may risk future yields. On the other hand, breach of contract often results in significant financial losses for the farmer. Increasing awareness and understanding of the importance of soil structure for soil function and yield potential could help to increase flexibility in contracts. Furthermore, the flexibility of contracts between farmers and traders should be enhanced, especially for crops that are more vulnerable to weather variability.

10. Does soil classification based on soil texture lose the information needed for soil structure management?

For agricultural purposes and within farmers and advisory services, soils are often classified according to their texture (particle-size distribution). However, the proportion of clay, silt and sand does not reveal soil characteristics related to parent material, climate, relief or resulting from the age of the soil (soil forming factors). Classification systems like World Reference Base which consider the diagnostic characteristics and their relationship with soil-forming processes can better reveal conditions in soil related to soil wetness or properties originating from the quality of the parent material (Gray et al. 2011). People responsible for soil management decisions should be better informed about the role of soil-forming and soil health related factors in shaping soil characteristics across different climates and topographical locations.

3.3 Overview

An overview of the knowledge gaps can be found under Suppl. material 1

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Supplementary material

Suppl. material 1: Overview of the knowledge gaps doi

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