Soil health – human health:
why soils are important for human wellbeing

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Table of Contents

Executive Summary

Soil is the basis of terrestrial life. It is one of the most complex ecosystems on earth, consisting of a variety of minerals, soil organic matter, water, air, and a huge biodiversity of organisms. Particularly microorganisms are key drivers of soil functions and ecosystem services. Soil enables agriculture, supports the formation of drinking water, provides space for human activities and is one of the largest carbon pools on earth.

Due to human activities, soil is severely threatened. Soil degradation and soil losses endanger soil as a natural resource. Erosion, compaction, contamination, and soil sealing are some processes which threaten not only ecosystem functions of soil, but also agricultural production and thus the main foundation of human wellbeing. Not only the quantity, but also the quality of agricultural products is impacted by degraded soils, resulting in reduced nutritional quality and enhanced contaminant concentrations. The filter capacity of soils is the basis for clean drinking water production. Degraded soils are restricted in their ability to retain pollutants, thus leading to drinking water pollution. Drinking water quantity is increasingly affected too, since the capacity of water uptake reduces when soil quality deteriorates. Soil microorganisms are not only key players in soil processes, but also comprise the ultimate source for microorganisms in the human body, particularly in the gut. Food is the major factor determining microbial diversity in the gut. Over the last decades, intensive agriculture has caused a reduction of microbial diversity in soils and thus also in crop plants. This, in combination with intensive food processing, has led to a decline in microbial diversity in human guts, which has vast effects on human health.

It is therefore crucial to implement measures that reduce soil degradation and improve soil quality. In the agricultural sector, these measures should focus on (1) keeping soils covered as much as possible, (2) minimizing soil disturbance, (3) growing a diversity of plants, (4) continuously maintaining living roots throughout the year and (5) integrating livestock into agroecosystems. This can be reached via organic fertilization and focusing on measures that support the accumulation of soil organic matter – which, in turn, aids the soil microbiome and physicochemical qualities related to healthy food production and water filtration These measures include for example a well-designed crop rotation, cover crops and intercropping. Policy should support conservation tillage and biological plant protection instead of agrochemicals. Schemes to aid the recognition and implementation of agroforestry systems and water harvesting methods could further support soil health in agroecosystems. For grasslands, extensifying grazing and mowing is crucial, e.g. via rotational grazing and/or rewetting projects. The Common Agricultural Policy (CAP) is one main instrument which should be adapted to support soil health.

Sarah Wiener

In forestry, it is recommended to (1) increase tree biodiversity by converting forests from monocultures to regionally adapted mixed cultures and (2) optimize tree harvesting approaches. This could include prohibiting clear-cuts and switching to single tree harvesting, optimizing harvesting times (e.g. only in winter when soil is frozen) to avoid compaction, well-planned harvesting routes and adapting rotational periods to the frequency of natural disturbances. Full-tree-harvesting should be prohibited, so that organic residues and deadwood remain in the forest. Preventing and managing forest fires is another key component of supporting soil health in forests, and extensivation and rewetting projects could yield benefits for forest soils too.

In urban areas key approaches in soil protection and soil quality improvement are (1) the establishment of stormwater flood protection measure related to soil surface permeability, (2) enlarging the vegetational cover to compensate urban heat island effects and (3) the (bio)remediation of contaminated soils. Stormwater flood protection systems should be based on the concept of "Sponge Cities", meaning the protection of and regulations for minimum requirements of surface permeability. Nature-based Solutions like green infrastructure oriented towards water retention can both aid flood protection and reduce heat islands effect and should therefore be supported and included in strategic urban planning. Setting aside unused land and/or old infrastructure could be another way of increasing the vegetational cover in highly populated areas. Bioremediation methods should focus on the bioavailability of contaminants rather than their total concentration – possible measures are plant-based approaches like phytoremediation, phytostabilization or phytomanagement. Brownfield revegetation could be a valuable option for reducing total land use and thus reduce soil sealing.

Action is needed and urgent, since soil degradation is an ongoing process which puts soil and its wide-ranging functions as base for food production and drinking water, as part of carbon storing ecosystems, water cycles, local cooling and air purification at risk. Proper monitoring of pressures, the application of specific, tangible measures within frameworks and guidelines and usage of regulations could promote soil health and thus human health in Europe.

1

Introduction

Soil – a complex and precious resource

Soil is the fundamental basis of terrestrial life. It is a thin layer that covers the earth crust, often less than a meter thick. It is one of the most complex ecosystems on earth and hosts an enormous biodiversity of microorganisms, fungi, algae, and animals, and it supports terrestrial plant life, including agriculture.

Soil is a **highly complex material,** consisting of inorganic and organic components. Inorganic components include soil minerals, water, and air. Organic components comprise soil organic matter (SOM) and all living organisms. The solid particles of the soil are grouped and form a porous system offering huge surfaces. These are the habitat for an enormous amount of soil organisms. There may be over 1 million different groups of organisms in just 1 teaspoon of soil, the majority being microbes.[1]

Soil supports a range of **ecosystem functions** but is also fundamental for human prosperity. Soil is vital for food security and environmental stability, but also for the generation of clean drinking water, and it provides space for various human activities. After the oceans, soil is the largest carbon pool on earth. In this context, soil health can be defined as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans”.[2]

Most soil functions depend on the soil’s health – a thriving soil with a flourishing microbiome and many interaction processes between soil-plant-water-atmosphere is the backbone for soil functions supporting human health. Functions include filtering, buffering and transformation of substances like nutrients and contaminants, which ensures nutrient cycling and purity of water. Soil also provides the base for food production and safety, an essential part of human wellbeing. Several functions support each other and are intertwined, making soil a highly complex, living meta-organism – like humans themselves. The different parts of soil (particles, organisms, air, water) do not simply coexist but are strongly linked to one another by several processes. Most interactions between organisms, nutrients and contaminants occur in the pore space between soil particles. Those interactions determine how many nutrients and contaminants occur in the soil water - which is crucial for nutrient and contaminant uptake into plants or transport to other ecosystems like the atmosphere or water bodies. Depending on the location, parent rock material, local climate and the inherent soil characteristics, there are many different soil types providing different ecosystem services. Soils are dynamic systems, where a healthy soil represents a well-balanced soil in its components, organisms and the interactions between them.[3]

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[1] **van Gestel, C.A.** C.A. et al. (2021) Soil Biodiversity: State-of-the-Art and Possible Implementation in Chemical Risk Assessment. Integr Environ Assess Manag. 17, 541-551.

[2] U.S. Department of Agriculture (2019) Natural Resources Conservation Service. Soil Health, *https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/*. Accessed 18/08/2023.

[3] **Keesstra, S.** Keesstra, S. et al. (2021) The role of soils in regulation and provision of blue and green water. Phil. Trans. R. Soc. B., 376.

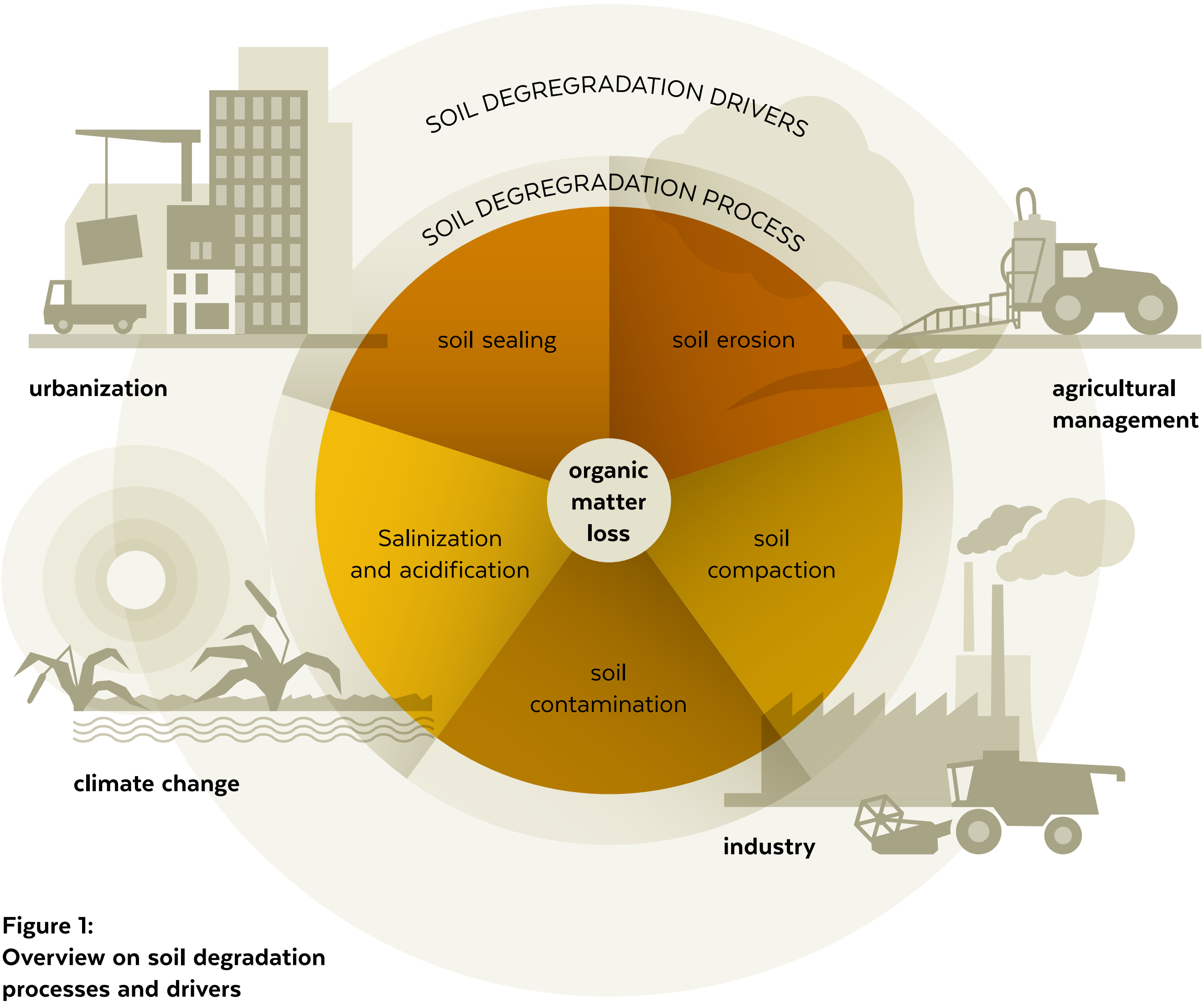

Figure 1:
Overview on soil degradation processes and drivers

Soils under risk – degradation processes

Although soil is such a fundamental natural resource for human prosperity and well-being, it is under severe threat. Intensive agriculture, urbanization, industrial activities, etc. have led to **soil degradation and soil loss.** Erosion by wind and water, but also soil sealing lead to loss of soil. Soil organic matter (SOM) degradation, compaction, salinization, acidification, and contamination as well as compaction are major drivers of soil degradation. Consequently, soil is disturbed in its functioning, which has a range of negative impacts on ecosystem services, but also on its functions that are fundamental for humans. For example, the conversion from natural to agricultural soils and deforestation, and also intensive use of soils lead to massive losses of SOM and carbon stocks. This alters a range of processes and interactions in the soil – often leading to reduced soil stability and fertility. In addition, within already existing agroecosystems soil is under the threat of degradation: agrochemicals like fertilizers or pesticides, monocropping and overgrazing deprive soils of their organic matter, leading to a depletion of the very much essential microbiome. The main threats for European soils are presented in the following.

One of the major processes of soil degradation is **soil sealing**[4] – the process of covering soil with a non-permeable material like concrete or asphalt. During the years 2012-2018, ca. 400 km² of soil was consumed via sealing – each year.[5] Sealing eliminates nearly all soil functions at once, since it cuts off all interactions with water, air, and plants. Main drivers are industrial and urban development as well as infrastructures related to mobility and tourism.

Soil sealing results in an irreversible loss of all soil functions:[6]

- makes food production impossible, especially when fertile soils are sealed
- eliminates water infiltration and storage, generating surface runoff and increasing flood hazards

- cancels local climate regulation: without vegetation the temperatures of surfaces rise, leading to the urban heat island effect
- erases filtration, immobilisation, and purification capacity for organic and inorganic contaminants
- makes carbon sequestration and storage impossible
- wipes away habitats for soil organisms, plants and animals through destruction and fragmentation, leads to loss of biodiversity
- diminishes landscapes and cultural heritages

Sealing and limited surface permeability due to, e.g., concrete, make cities hotspots for flooding and heat islands effects. This is especially alarming considering the high population density in European cities and the possible threats to livelihood securities that come from flood and heat risks. Limiting sealing and restoring soil water uptake capacities are therefore highly important in urban areas. Concepts like "Sponge Cities" focus on reversing sealing and preserving permeability of soils to aid flood and heat protection. The main goal is for soil to be able to take up and store plenty of water (like a sponge). More vegetational cover and permeable surfaces like grass-gravel mixtures or permeable pavements can reverse and/or limit soil degradation in expanding and heavily sealed cities (more details from page 36).

Erosion is another important degradation process[7] – approximately one billion tons of soil are eroded each year in the European Union (EU).[8] It typically occurs on soils with no or little vegetation cover and reduced structural stability in combination with heavy rainfall or strong winds.[9] Due to erosion, soil particles - and with them nutrients and organic matter – are irreversibly lost to other ecosystems, e.g. water bodies, where they may cause severe problems, such as algal blooms. Soil loss is a huge problem in agriculture, as the formation of 1-10 cm fertile soil requires several thousands of years. Soil fertility may severely suffer from erosion processes.

Soil compaction is another very common issue, especially for agricultural soils and is caused by using heavy machinery, tilling, and overgrazing. Around 23% of the EU's soils are critically compacted.[8] It disrupts soil structure and reduces porosity and permeability and thus lowers water infiltration and storage capacity. This leads to increased surface runoff or waterlogging, enhanced erosion, landslides, and flooding.[10] Moreover, compaction increases resistance to root penetration, affects nutrient and gas exchange (lack of oxygen can enhance greenhouse gas emission) and impairs soil biodiversity. Compaction-induced soil cracks also cause contaminant transport to deeper soil layers and groundwater. All these effects of compaction on soil functions result in reduced crop yields by 2.5-50%, reduction of soil trafficability and number of workable days. Impacts are often irreversible or last over decades.[11]

Industrial activities, mining and landfills may **contaminate soils** as heavy metals and organic contaminants are released, strongly affecting not only soil health but also human health. Depending on the soil's properties, type and concentration of contaminants, the soil can lose its capacity to filter and retain (buffer) contaminants. The deposition of contaminants alters the soil's physical, chemical and biological properties, e.g. lowering microbial activity, altering community structure and reducing biodiversity. This can affect soil organic matter and soil stability, thus enhancing erodibility and consequently the risk for spreading contaminants and contaminated soil over broader areas and to water bodies.

Irrigation, inappropriate drainage systems, groundwater over-exploitation and sea-level rise lead to **soil salinization.** An excess concentration of salts in soils alters microbial metabolism, affects nutrient decomposition and ultimately limits soil fertility. This in turn reduces plant health, yields, and makes soil more prone to erosion and further degradation.

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[4] **Dragović, N.,** Vulević, T., (2020) Soil Degradation Processes, Causes, and Assessment Approaches, in: Leal Filho, W. et al., Life on Land. Springer International Publishing, 1–12

[5] European Environment Agency (2023) Land take and net land take. *https://www.eea.europa.eu/data-and-maps/dashboards/land-take-statistics#tab-based-on-data. Accessed 13/10/2023*

[6] **Ferreira, C.S.S.** et al. (2022) Soil Degradation in the European Mediterranean Region: Processes, Status and Consequences. Science of The Total Environment 805.

[7] IPCC (2019) Land Degradation. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

[8] European Environment Agency (2023) Land take and net land take. *https://www.eea.europa.eu/data-and-maps/dashboards/land-take-statistics#tab-based-on-data. Accessed 13/10/2023*

[9] **Panagos, P.** et al. (2015) The new assessment of soil loss by water erosion in Europe. Environ Sci Policy 54, 438-447.

[10] **Schjønning, P.** et al. (2015) Driver-Pressure-State-Impact-Response (DPSIR) analysis and risk assessment for soil compaction-a European perspective. Advances in Agronomy 133, 183-237.

[11] **Ferreira, C.S.S.** et al. (2022) Soil Degradation in the European Mediterranean Region: Processes, Status and Consequences. Science of The Total Environment 805.

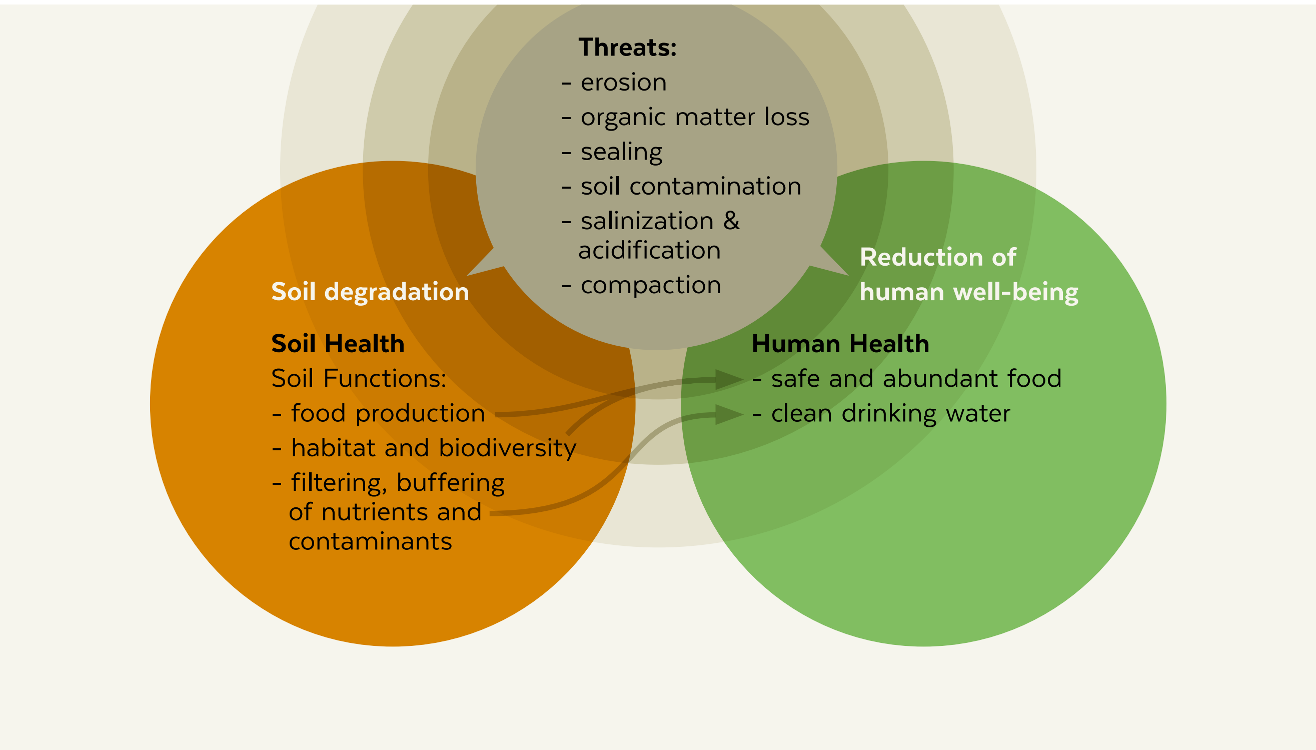

Figure 2: Threats to soil and their effect on human well-being

Most of the above-mentioned degradation mechanisms ultimately lead to the **degradation of soil organic matter** (SOM), which is a hub for many crucial soil functions and the base for soil fertility. Degradation of SOM limits abundance and diversity of the soil microbiome which drives nutrient cycling, carbon sequestration and crop nutrition. A lack of SOM decreases filter and buffer capacities and heavily reduces water uptake and storage in the soil. Organic matter is also the structural backbone of soil – if it is depleted, the soil is more vulnerable to further degradation and perturbations.

Lastly, human-made **climate change** also influences soil degradation. It exacerbates already existing pressures on soil and introduces new degradation processes. Impacts arise from higher temperatures, changes in precipitation and wind and more frequent and intense extreme weather events.[12] The combination of those factors increases already existing problems like those of soil erosion via wind and water. After longer periods of drought the soil can only take up little water (like a very dry sponge). If then a heavy rainfall event happens, most of the water cannot infiltrate into the ground, but is washed away on the surface, sweeping away soil particles. Generally, heavier rainfall carries away more soil particles and logs the soil with water, which can cause many problems for agriculture. Also, those extreme events make landslides and drastic land degradation more likely, affecting the health and safety of humans. One extreme event, e.g. very heavy rainfall, can have an impact on the landscape for several decades. Especially the Mediterranean region will face more pressures like those.[13] Climate change also brings more intense winds and storms, which will likely further accelerate erosion – especially on agricultural land, if the ground is uncovered (i.e. no vegetation): soil loss rates will increase by more than 50% in many areas with ongoing climate change.[13] Increased irrigation as a result of more frequent and intense drought events may lead to salinization of soils. In addition, fire events in managed areas like forests and cropland will increase with climate change and intensify soil degradation.[13] Climate change also leads to shifts in the microbial communities of soils, which most often leads to a depletion of soil organic matter (SOM). Changing temperatures and altered microbial activity disrupt cycling of organic matter in the soil system – in many cases, more organic matter is transformed to greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), amplifying climate change. Thus, many degradation processes in one way or the other affect SOM and link soils and the climate system.

Soil degradation puts human health and wellbeing at risk – not only during extreme weather events, but also in the context of food and water safety. Climate change makes this topic even more acute – however, management options can reduce or reverse land degradation and its threatening impacts (see chapter 5 for management implications).

Soil health for planetary health and human prosperity

The importance of soil and the far-reaching consequences of soil degradation make it **central element of the United Nations Sustainable Development Goals (UN SDGs).** These offer a “blueprint for peace and prosperity for people and the planet”, and soil plays a central role in reaching that: e.g. in SDG2 (zero hunger), SDG3 (good health and well-being, including reduction of risks from air, water and soil pollution), SDG 6 (clean water and sanitation), SDG13 (climate action, e.g. enhance soil carbon sequestration) and SDG 15 (life on land)[14]. As the backbone for food security, soil health supports nutrition and is a central element of sustainable agriculture (SDG 2). It helps ensuring availability and sustainable management of safe drinking water (SDG 6) and is central to reverse land degradation (SDG 15).

As explained above, soil offers diverse ecosystem services and functions, on which humans are directly or indirectly dependent. **Soil essentially is the base of planetary life** and human health. Human health was defined in 1948 by the World Health Organization (WHO) as “a state of complete physical, mental and social wellbeing, and not merely the absence of disease or infirmity”.[15] Later, the concept of One Health was developed, considering that human health is not isolated, but connected to the health of plants, animals, and the environment.[16] Among other factors, human health is largely dependent on soil health. The interdependence between soil characteristics, soil processes and human health will be assessed in this paper.

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[12] IPCC (2019) Land Degradation. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

[13] **Li, Z.** and **Fang, H.** (2016) Impacts of climate change on water erosion: A review. Earth-Sci. Rev. 163, 94–117.

[14] **Rodrigo-Comino, J.** et al. (2020) Soil Science Challenges in a New Era: A Transdisciplinary Overview of Relevant Topics. Air, Soil and Water Research 13.

[15] World Health Organization (1946) Constitution of the World Health Organization, *http://apps.who.int/gb/bd/PDF/bd47/EN/constitution-en.pdf.* Accessed 18/08/2023.

[16] *https://www.who.int/news-room/questions-and-answers/item/one-health.* Accessed 18/08/2023.

2

Soil and water quality

Soil systems are of key importance fo **water regulation and purification,** and soil quality determines the quality of surface and ground water. Surface water like rivers and reservoirs supply 75% of European freshwater, while 25% stem from groundwater.[17] European drinking water originates to 65% from groundwater.[18] Major threats to European water bodies are overexploitation and pollution. Healthy soils play a crucial role in the water cycle as they regulate rainwater infiltration (process by which water on the soil surface enters the soil) and store water that is available to plants, prevent floodings and landslides and filter water before it reaches the groundwater. However, the soils' capacity to fulfil these functions is limited. Intensive agriculture, urban development, industry, mining and mismanagement of waste put pressure on soil-related water quality and quantity. Sealing, compaction, and soil cultivation affect water uptake, water holding capacity, water percolation and water filtration.

Interactions between water and soil

The water cycle comprises evaporation from oceans, seas and lakes, plant uptake and transpiration (water vapour released from leaves to the atmosphere), condensation, precipitation, infiltration, and percolation in soil for intermediate storage or transport to groundwater. Generally, the behaviour of water in soil is determined by the soil's texture (i.e. the particle size distribution among major inorganic soil components such as sand, silt and clay) and structure (particle arrangement, i.e. size and shape of aggregates that are granules made up of sand, silt and clay glued together by organic matter), which together with roots and soil dwelling animals like earthworms create a **pore system with many functional surfaces.** These influence water uptake, storage, availability for plants and transportation to deeper layers. A healthy soil has a high **aggregate stability,** as soil organisms such as bacteria, fungi, earthworms, and plants excrete compounds that bind soil particles together. Soils with a diversity of stable aggregates are well-structured and can absorb and contain more plant-available water, because of a higher infiltration rate, greater water-holding capacity, better structure and aggregate stability, greater macroporosity, which lower the risk for runoff and erosion.[19] However, not only the aggregates, but also the soil's particle size distribution determines the dynamics of water in soil. In sandy soils water quickly moves through soil, water storage is low, and it dries up fast. Soils with a high clay content store more water but rain infiltrates more slowly and often runs off leading to soil erosion. The addition of **organic matter supports stable aggregate formation** to render the soil more resistant to compaction and increases water retention and storage.

Water is a key force in soils – it is crucial for particle and compound (including nutrients and contaminants) transportation within the soil, but also on the soil surface. The **soil's pore system filters water** mechanically, chemically, and biologically. **Reactive surfaces** along pores retain nutrients and contaminants from soil water. Transformation of substances in soil influences their solubility, availability to plants and microorganisms and their mobility in soil and towards aquatic systems. **Microorganisms** living in soil pores or around roots can degrade organic pollutants, immobilize contaminants and excessive nutrients, and thus prevent groundwater pollution. The efficiency of soil as a filter depends on soil properties, in particular on the microbial community composition and activity, but also on the behaviour of pollutants.

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[17] *https://water.europa.eu/freshwater/europe-freshwater/freshwater-themes/water-resources-europe.* Accessed 04/09/2023.

[18] European Environment Agency (2022) Europe's Groundwater : A Key Resource under Pressure (Office des publications de l'Union européenne), https://doi.org/10.2800/50592. Accessed 04/09/2023.

[19] **Keesstra, S.** et al. (2021) The role of soils in regulation and provision of blue and green water. Phil. Trans. R. Soc. B 376.

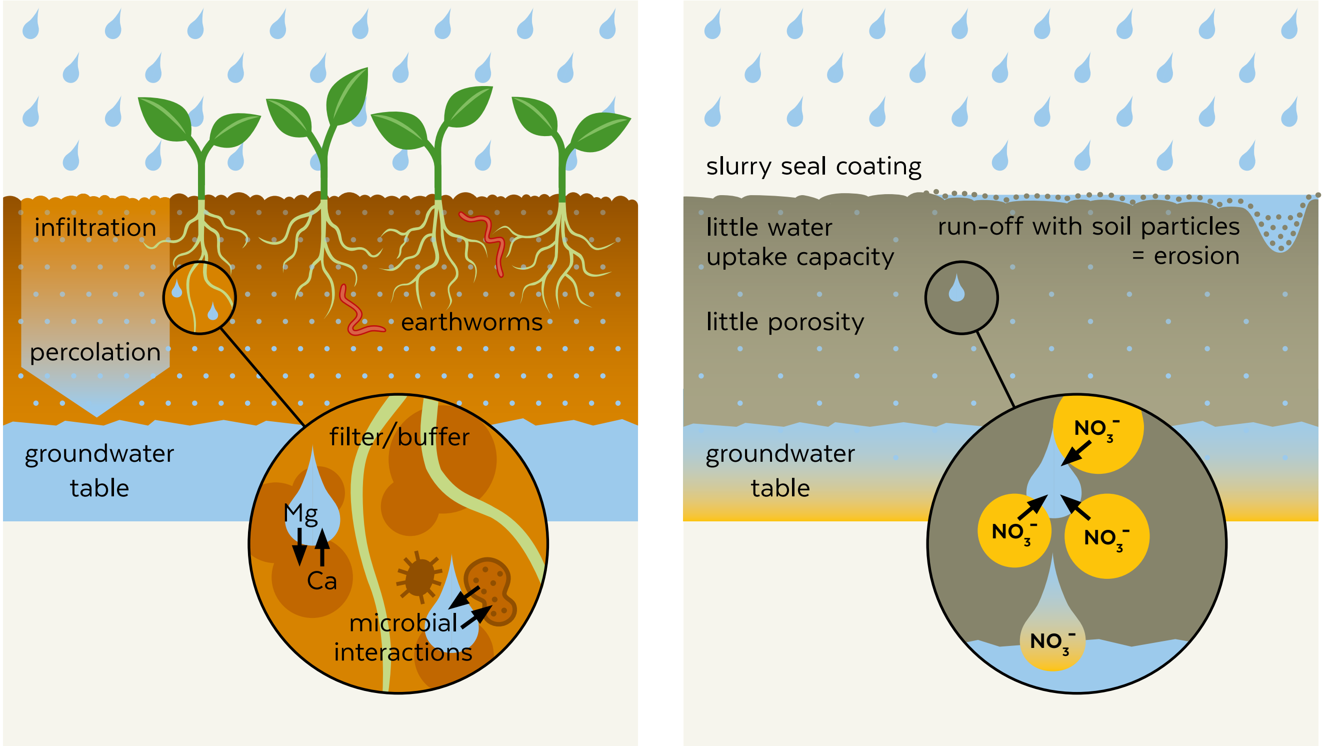

Figure 3:
Interactions between water and soil

Leaching is a process where nutrients and contaminants are carried through the soil downwards into the groundwater with rain or irrigation water (see below). **Erosion** is a major pathway for nutrients and contaminants attached to soil particles that end up in surface waters like rivers and lakes and finally in coastal waters. This can pollute water bodies and lead to eutrophication and algal blooms, resulting in oxygen depletion and the release of toxic compounds threatening aquatic ecosystem functions, but also human safety and health. During erosion, soil is swept away with water that runs off on the soil surface leading to soil loss. This process may be triggered by reduced water uptake capacity of a soil – a degraded soil with a damaged pore system or a very dry soil is strongly limited in its capacity to take up loads of water. The kinetic energy of raindrops may destroy soil aggregates, clog the pores, leading to the formation of a sludge, which seals the topsoil and prevents water infiltration during future rainfall events and intensifies erosion – this process is called **slurry seal coating.** If the capacity of the soil to infiltrate large amounts of water is limited, the water and the surface of the soil is washed away, leading to erosion, soil loss and eventually to **eutrophication and clogging of waterways or infrastructures** (e.g. sewage systems).

A stable and well-developed **plant cover is key for reducing erosion:** plant leaves deaccelerate the force of raindrops and allow for a slower and therefore more efficient infiltration of rainwater. Moreover, the roots also stabilize the soil, allowing it to take up and store more water. Without a vegetational cover, soil structure and pores can be destroyed by the kinetic energy of raindrops, as explained above. Ultimately, **high organic matter content and building up soil organic matter** are fundamental for reducing erosion risks as organic matter stabilizes soil structure for water infiltration and increases water holding capacity.

Soil-related threats to water resources

The main stressors for water quality are **agrochemicals** like fertilizers and pesticides and their metabolites (intermediate decomposition products), especially because they are applied on a large scale causing non-point contamination that is difficult to manage. Moreover, soil life is often negatively affected by agrochemicals, reducing the soil functions and the soil's resilience towards stressors.

Nitrogen and phosphorus are essential macronutrients for life on Earth, but in the last decades excess fertilizer application and urban and industrial waste accumulation has led to dramatic discharge of these nutrients from soils to aquatic ecosystems and to the atmosphere. Generally, only 35% of nitrogen[20] and 12% of phosphorus[21] from mineral fertilizers end up in the crops; this highlighting huge inefficiency and dramatic losses. Plants either directly take up inorganic nitrogen and phosphorus dissolved in the soil water, i.e. nitrate, ammonium, and phosphate, or plants acquire these nutrients from less available organic sources due to microbial mineralization processes in the soil surrounding roots. The exploitation of these interactions is especially important to increase nutrient cycling and reduce mineral fertilizer use as the latter contributes to the decline of soil biodiversity and water quality. Nitrate is weakly retained by the soil and thus may easily leach to groundwater with irrigation water or rain. Under conditions promoting microbial activity (warm temperatures, adequate soil moisture, tillage) nitrogen can be transformed to greenhouse gases, e.g. nitrous oxide, which escape to the atmosphere.[22] Phosphate strongly interacts with soil and is rapidly immobilized by microbial uptake. In contrast to nitrogen, phosphorus is less prone to leaching but susceptible to transportation to aquatic systems during soil erosion events.

Nitrogen and Phosphorus from manure and plant residues can be converted by microorganisms into inorganic and thus plant-available forms with a time lag. This process is called mineralization. In contrast to mineral fertilizers, nutrients bound in organic matter are released only gradually, which reduces the susceptibility for leaching. However, even organic fertilizers require careful management. If no (cover) crops take up the mobilized nutrients, these can also leach to groundwater or may be washed away with soil particles to rivers and streams. This is the case especially in late autumn, mild winter, and early spring, when microbial activity is still high, and the vegetation cover is reduced or even completely removed.

In lakes and oceans, excessive nitrogen and phosphorus cause pollution and eutrophication leading to excessive growth of algae which excessively consume oxygen and produce toxins. These toxins can accumulate in mussels and fish. The consumption of contaminated sea food can then cause severe illnesses in humans ranging from gastrointestinal problems to cardiovascular diseases, long-term neurologic symptoms and even death.[23] The frequency and intensity of harmful algal blooms will likely increase with climate change, consequently affecting the recreational and economic value of coastal regions.

Legal threshold values for **nitrate in drinking water** were set to protect babies from methaemoglobinaemia (blue baby syndrome), but even lower nitrate concentrations can already cause human health risks like cancer and heart diseases.[24] Nitrogen levels in the groundwater have already been increasing over the last years[25] due to excess nutrient inputs and accumulation (legacies) and current soil mismanagement.

Managing nutrient contaminations is challenging, since this kind of pollution is typically not only influenced by current but also a result from past fertilizer applications. Nutrients have accumulated in oils due to excess nutrient input and fixation on the soil. These so-called legacies can easily be remobilized and transported to water bodies with a time lag. This also means that the impact of current and future European Union (EU) policies (e.g. reducing fertilizer use by 20% to reduce nutrient losses by 50% until 2030) will not be effective immediately and is difficult to monitor. These legacy nutrients within the widespread catchment area of rivers make freshwater quality targets (e.g. Water Framework Directives, EU Green Deal) highly difficult to achieve.[26]

The widespread application of **pesticides** to protect crops from insects, weeds and fungi has led to high concentrations of pesticides and their metabolites in 13-30% of all European surface and groundwaters between 2013 and 2019.[27] While most pesticides are used in the agricultural sector, industrial sources like the wood industry or household gardening also are non-negligible sources. Pesticide formulations contain high concentrations of organic compounds such as chlo-

[20] **Omara, P.** et al. (2019) World Cereal Nitrogen Use Efficiency Trends: Review and Current Knowledge. Agrosystems Geosci. Environ. 2, 1–8.

[21] **Yu, X.** et al. (2021) Global analysis of phosphorus fertilizer use efficiency in cereal crops. Global Food Security,

[22] **Cameron, K. C.** et al. (2013) Nitrogen losses from the soil/plant system: a review: Nitrogen losses. Ann. Appl. Biol. 162, 145–173.

[23] **Grattan, L. M.** et al. (2016) Harmful algal blooms and public health. Harmful Algae 57, 2–8.

[24] **Ward, M.** et al. (2018) Drinking Water Nitrate and Human Health: An Updated Review. Int. J. Environ. Res. Public. Health 15, 1557.

[25] **Harrison, P. A.** et al. (2021) Identifying and prioritising services in European terrestrial and freshwater ecosystems. Biodivers. Conserv. 19, 2791–2821.

[26] **Bieroza, M. Z.** et al. (2021) What is the deal with the Green Deal: Will the new strategy help to improve European freshwater quality beyond the Water Framework Directive? Sci. Total Environ. 791, 148080.

[27] European Environment Agency (2022) Europe's Groundwater : A Key Resource under Pressure (Office des publications de l'Union européenne) Accessed 04/09/2023.

rinated hydrocarbons, organophosphorus, carbamate, but also some toxic heavy metals and metalloids such as copper, lead, mercury and arsenic. Their fate and transport depend on the pesticide's properties such as solubility in water, persistency against degradation and interaction with soil particles. Pesticides not taken up by plants are either retained by soil or degraded into other chemical forms with different solubility and toxicity than the initial compound. Soluble pesticides can leach to groundwater during precipitation events. Insoluble pesticides can be tightly bound to soil particles and accumulate in topsoil, where they can be transported to surface waters during erosion or be degraded to more soluble forms and leach to groundwater over times. Newly introduced pesticides reduce enzymatic and microbial activity and can have toxic effects for certain organism groups. With repeated application, some microbial communities seem to adapt to the given substance – partly microbes metabolize and degrade pesticides, using their metabolites for their growth. Pesticides thereby shift microbial communities as well as their activity and can influence microbial nutrient cycling such as biological nitrogen binding. However, microorganisms can also become tolerant to pesticides, mainly as a cause of continuous misuse.[28]

Humans are exposed to pesticides through dermal contact or inhalation, especially during applications, or through ingestion of food (see chapter 3) and drinking water. Associated health risks include immunosuppression, hormone disruption, reproductive disruption, cancer, neurological effects, asthma, and acute effects like headaches, nausea, diarrhea, vomiting, coma and even death.[29] Removing pollutants from drinking water is very costly and not all substances are extractable.

Alternatives are biopesticides which are less toxic, more specific to target pests, effective in low doses or rapidly degraded. Examples are microorganisms like viruses, bacteria, fungi, or herbal pesticides which produce naturally pest-repelling chemicals.[30]

Antibiotic residues in manures deriving from pharmaceuticals applied to farm animals affect soil health and water quality. Manure fertilization to increase nutrients and organic carbon in soil may also cause input of antibiotic substances, bacteria and genes that are resistant to antibiotics as well as heavy metals (copper, zinc) or disinfectants. In soil, the fate of veterinary antibiotics depends on reactions with the soil solid phase (sorption), microbial or physical transformation and mineralization to inorganic compounds. However, mineralization affects just a small amount of added antibiotics (less than 2%), while a large fraction is bound by the soil or trapped in small pores (sequestered) and thus protected from microbial degradation. This leads to accumulation of antibiotics in soil and potential release over time. Some compounds are prone to leaching to the groundwater, but surface runoff and transport of antibiotics with soil particles to surface water bodies is a major pathway of antibiotics to affect water quality. Moreover, antibiotics alter soil microbial composition and activity as some groups of organisms (taxa) are enriched while others are suppressed, and antibiotic-resistant bacteria or genes are introduced with manure. This influences the complex regulatory network of the soil microbiome affecting processes such as microbial nutrient cycling, pollutant degradation and plant growth promotion. The effects of antibiotics on soil microbial community might only be temporary as the abundance of resistance genes may decline over time and thus enable the soil microbiome to restore. However, the consumption of resistant bacteria with uncooked vegetables or fruit can affect the human microbiome and lead to the threat of incurable infections in humans (compare chapter 4).[31] Antibiotic resistance is one of the topics in which the concept of "One Health" is the most obvious – this global problem does not only influence humans, but also the environment and animals[32] (as described above). The improper management of antibiotics, often in the realms of animal husbandry, has a systemic effect of spreading of antimicrobial resistance into all actors involved in One Health, often in unforeseeable patterns and ways. This makes infection and disease control for human and environmental health extremely challenging and stresses the need for holistic approaches.

Micro- and nanoplastics are formed when plastic is mechanically or photochemically degraded into smaller particles that may also become biologically active. Examples are phthalates, bisphenols, polyethylene,

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[28] **Wołejko, E.** et al. (2020) Soil Biological Activity as an Indicator of Soil Pollution with Pesticides – A Review. Applied Soil Ecology 147: 103356. https://doi.org/10.1016/j.apsoil.2019.09.006.

[29] **Syafrudin, M.** et al. (2021) Pesticides in Drinking Water—A Review. Int. J. Environ. Res. Public. Health 18, 468.

[30] **Rad, S. M.** et al. (2022) Water Pollution and Agriculture Pesticide. Clean Technol. 4, 1088–1102.

[31] **Jechalke, S.** et al. (2014) Fate and effects of veterinary antibiotics in soil. Trends in microbiology 22, 536-545.

[32] **Velazquez-Meza,** M.E. et al. (2022) Antimicrobial resistance: One Health approach. Vet World 15, 743-749.

polyvinyl chloride, polystyrene, polyurethane, polycarbonates. Some are carcinogenic, endocrine-disrupting (hormonally active) or neurotoxic chemicals. However, information on adverse effects of microplastic in the human body is still limited and some effects derive from pollutants and pathogens bound to plastics. Humans are exposed to soil-derived nano- and microplastics through sea food, inhalation of contaminated soil dust or drinking water.[33] Sources include the direct application as plastic mulch, greenhouse buildings or soil conditioners (e.g. unpacked food or plastic bags in compost or fertilizers from biogas or sewage treatment plants). However, indirect release – especially from tire abrasion on roads, wastewater and accidents – are also important drivers for microplastic pollution of soils [34]. Soils, rivers, lakes, and oceans are the final sinks, but the plastics are quite mobile between ecosystems. Due to the small size micro- and nanoplastics have already migrated to many groundwater bodies. Plastic retention and movement in soils depend on soil-plastic interactions and degradation and transformation.[35]

Heavy metals and metalloids derive from fertilizers, sewage sludge, atmospheric deposition of traffic and industrial exhaust or dust from mining sites. Therefore, these pollutants typically accumulate in topsoil. In contrast to organic pollutants, metals and metalloids cannot be degraded in soil. Depending on their bioavailability, these metals may be taken up by crops and finally end up in the human food chain. In the long-term this may cause chronic metal toxicity diseases. The long-term exposure to cadmium-rich food may for example kidney diseases or bone softening. In the case of severe pollution, soil microorganisms or plants may even suffer from acute toxicity, leading to reduced microbial functioning on the one hand and reduced plant growth on the other. Via wind and water erosion, metal pollutants may also be transported to water bodies or accumulate as dust in housing areas. In soils with limited buffer function, metals may also leach to groundwater bodies, posing again a threat for human health.

[33] **Münzel, T.** et al. (2023) Soil and water pollution and human health: what should cardiologists worry about? Cardiovasc. Res. 119, 440–449.

[34] **Beste, A.** (2020) Leben im Plastozän. Der kritische Agrarbericht 2020. *https://www.gesunde-erde.net/media/beste_leben-im-plastozaen.pdf. Accessed 13/10/2023.*

[35] **Boyle, K., Örmeci, B**. (2020) Microplastics and Nanoplastics in the Freshwater and Terrestrial Environment: A Review. Water 12, 2633.

3

Soil and food quality

Soil forms the **base for food production and food security** and is thus closely linked to human dietary health. Only a healthy soil can provide a diversity of crops that contain all essential and beneficial nutrients in sufficient amounts, to support human wellbeing through the food we eat.

The nutritional quality of food

The **nutritional quality** of the food we eat is crucial for our dietary health. Micronutrient deficiencies challenge human health worldwide – also in the western world.[36] They are predominantly caused by an unsustainable diet consisting of ultra-processed foods – high in calories but low in nutrients – and a lack of vegetables and fruits. Apart from that, changes in the nutritional quality of the crops themselves due to **degraded soil contribute to deficiencies in the human diet.**

The **abundance and diversity** of minerals, vitamins, proteins and other macro-, micronutrients or trace minerals determine the nutritional quality of the food we consume. Furthermore, non-essential compounds like **Plant Secondary Metabolites (PSMs)** - also called Phytonutrients – are known for having great therapeutic health benefits for humans.[37] PSMs are a highly diverse group of metabolites found in soil and in plants – e.g. polyphenols, flavonoids, terpenes, and alkaloids. They reduce the impact of pathogens on humans, support immune system functions, have anti-inflammatory, antioxidative and probiotic effects and are expected to reduce the risk of cardiovascular diseases and cancer.[37, 38] Thus, Plant Secondary Metabolites are recommended to be included in frameworks for a healthy diet.[37] An overview of important nutrients, including phytonutrients, is shown in table 1.

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[36] **Ritchie, H.** and **Roser, M.** (2017) Micronutrient Deficiency. *https://ourworldindata.org/micronutrient-deficiency. Accessed 04/09/2023.*

[37] **Reeve, J.R.** et al. (2016) Chapter Six - Organic Farming, Soil Health, and Food Quality: Considering Possible Links. In: Sparks, D.L. (Ed.), Advances in Agronomy, Advances in Agronomy. Academic Press, 319–367.

[38] **Townsend, J.R.** et al. (2023) Foundational Nutrition: Implications for Human Health. Nutrients 15.

Nutrients			Function
Macronutrients – required in large amounts	Carbohydrates, Fats, Proteins		Main energy supply
Micronutrients – required in small amounts	Vitamins	Vitamins A, B, C, D, E, K	Diverse functions, e.g. support of metabolism and immune system
	Minerals	Calcium, Magnesium, Sodium, etc.	Diverse functions, e.g. as electrolytes, important part of numerous enzymes
	Trace minerals – required in very small amounts	Zinc, Iron, Iodine, etc.	Support immune system and cardiovascular health
Phytonutrients (PSMs)	Antioxidants	Polyphenols, Flavonoids, Terpenes, etc.	Anti-inflammatory effect, Probiotic effect, Support immune system Reduce impact of pathogens Reduce risk of cancer and cardiovascular diseases

Table 1:
Overview on the most important nutrients in human diet and how they are linked to human health.

Soil properties influence our food's nutritional quality

A healthy soil supports safe food – the other way round, a **contaminated or degraded soil jeopardizes food safety.** Pesticide residues on crops like fruits or heavy metals in vegetables can threaten the beneficial effects of the food we consume. Harmful substances can be taken up from the soil (e.g. heavy metals) but may also derive from direct application to the plant – as it is the case with the application of pesticides and other plant protectants. Whilst there is EU legislation on threshold values for harmful substances in food (Council Regulation 315/93/EEC), many crops, especially fruits like grapes and leafy greens like arugula, often contain alarming amounts of pesticide residues.

Several **soil characteristics influence crop quality** and thus the quality of the food we consume. A robust and intact system of plant-soil-microbes with an abundant, diverse soil life and multiple plant mechanisms is crucial in providing food of high nutritional quality. These soil health effects may reach far beyond the presence and supply of essential nutrients. High-quality soil offers a **high organic matter content** and an abundant and diverse microbiome, especially in the soil around roots, the so-called rhizosphere.[39] These microbes maintain a high metabolic activity and create a **nutrient-microbe synergy.[40]** In this synergy, nutrients cycle through the plant-soil-microbe system and provide optimum nutrient ratios, so called nutrient homeostasis, and their bioavailability.

Under those conditions, plants can take up all the mineral elements and produce all the vitamins and other nutrients we need: crops grown on healthy soils with an **abundant plant-soil-microbe system** are typically characterized by a higher content and quality of minerals, vitamins, trace elements and proteins compared to crops from degraded soils.[41][42][43][44]

This is especially relevant for Plant Secondary Metabolites (PSMs) – they are produced in plants surrounded by a healthy soil microbiome and in conditions of nutrient homeostasis.[43][44] PSMs primarily benefit plant

[39] **Reeve, J.R.** et al. (2016)

[40] **Townsend, J.R.** et al. (2023)

[41] **Reeve, J.R.** et al. (2016)

[42] **Aulakh, C. S.** et al. (2022). A review of the influences of organic farming on soil quality, crop productivity and produce quality. J. Plant Nutr. 45, 1884–1905.

[43] **Bertola, M.** et al. (2021) Improvement of Soil Microbial Diversity through Sustainable Agricultural Practices and Its Evaluation by -Omics Approaches: A Perspective for the Environment, Food Quality and Human Safety. Microorganisms 9.

[44] **Montgomery, D.R.** and **Biklé, A.** (2021) Soil Health and Nutrient Density: Beyond Organic vs. Conventional Farming. Front. Sustain. Food Syst. 5.

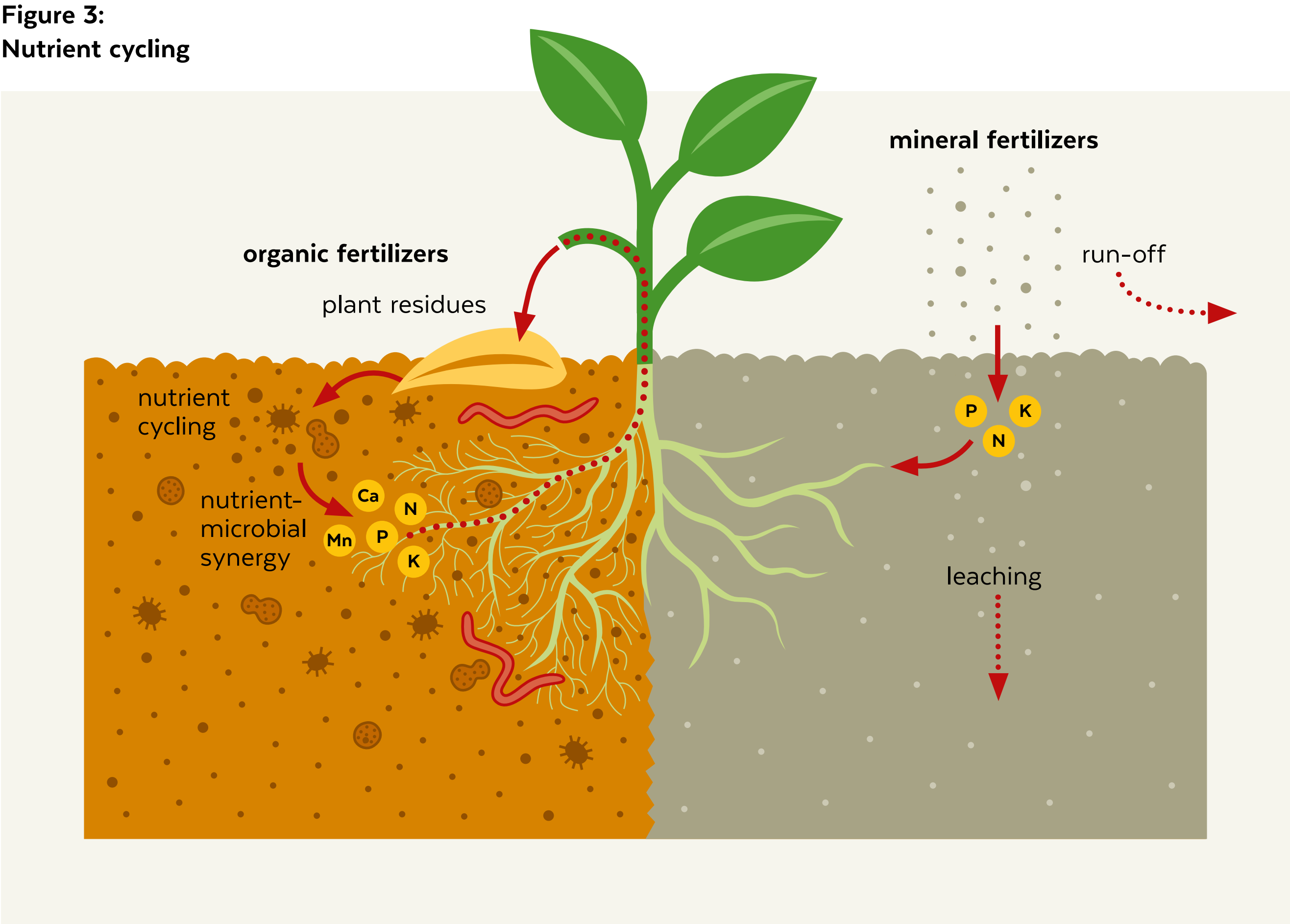
health, but also support human health and wellbeing after consumption. They are produced by plants as defense against pathogens, protection against environmental stress like drought or temperature extremes and for the attraction of beneficial organisms like pollinators and microbial symbionts.[45] PSMs enhance soil nutrient cycling by mobilizing nutrients and assisting the growth of beneficial bacteria which mineralize soil nutrients and make them plant available.[45] Apart from their supportive function, PSMs give vegetables and fruits their distinct color and taste: one example are vine grapes and berries, whose dark color results from PSMs.

Soil management influences on our foods' nutritional quality

Plants can only produce Plant Secondary Metabolites (PSMs) under certain circumstances – most importantly when their own defense mechanisms are active.[41 44 45] This is the case when a **healthy, diverse, abundant, and active microbial community** surrounds and colonizes the plant. Microbiome health in turn is dependent on the **abundance and quality of soil organic matter** (SOM) in the ground.

Widely used management techniques like **fertilization, application of pesticides and regular tillage** reduce SOM, degrade the soil microbiome,[41, 42, 44] and thus limit the production of PSMs and the uptake of minerals and vitamins. Pesticides for example fight pathogens, but replace natural plant defense mechanisms,[42] which means that less PSMs are produced – this way, the food lacks the health promoting benefits of, e.g. polyphenols. Plowing can fight weeds and prepare the soil for sowing but at the same time destroys the complex soil structure, reduces SOM content and alters microbial composition.[44] This in turn reduces water availability for the crop, slows down nutrient cycling and minimizes crop mineral uptake and Plant Secon-

Figure 3: Nutrient cycling



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[45] **Clemensen, A.K.** et al. (2020) Ecological Implications of Plant Secondary Metabolites - Phytochemical Diversity Can Enhance Agricultural Sustainability. Front. Sustain. Food Syst. 4.

dary Metabolite production.[43] Mineral fertilizers offer readily available macronutrients for plants (nitrogen, phosphorus, potassium), but shift nutrient ratios and thus dilute less mobile nutrients like micronutrients (e.g. iron, manganese).[41, 42] Consequently, crops take up less of those micronutrients and trace elements and develop a lower nutrient density. With the supply of readily available plant nutrients, mineral fertilizers starve the microbiome – which feeds on SOM. The readily accessible nutrients lead to **microbiome degradation** and thus soil degradation, change nutrient ratios, and interfere with natural plant defense mechanisms.[41, 42, 44] These processes reduce the nutritional quality of the crop and increase its susceptibility to diseases.[41]

Apart from soil management itself, the **choice of cultivar** also plays a crucial role in the nutritional quality of the crop – many older cultivars tend to have a higher nutrient density than modern cultivars.[46] For example, wilder forms of lettuce can have up to three times more beta-carotene, a powerful antioxidant, than modern lettuce cultivars.[47] This is also the case for staple crops like wheat: modern breeds have higher yields but a lower concentration of minerals. Consequently, we need larger amounts of food to ingest the same bulk of nutrients. For example, an average adult had to consume 10 slices of bread made from historical wheat cultivars to cover their recommended intake of zinc – today, they would already need 15 slices.[48] General **simplification and intensification of agricultural systems** (monocultures with little structural diversity) reduce the systems' plant diversity, which diminishes biochemical diversity and thus limits the production of PSMs and the availability of minerals and vitamins.[49]

[46] **Reeve, J.R.** et al. (2016)

[47] **Mou, B.** (2005) Genetic Variation of Beta-carotene and Lutein Contents in Lettuce. J. Am. Soc. Hortic. Sci. Jashs 130, 870–876.

[48] **Murphy, K.M.** et al. (2008) Relationship between yield and mineral nutrient concentrations in historical and modern spring wheat cultivars. Euphytica 163, 381–390.

[49] **Clemensen, A.K.** et al. (2020)

4

Soil microbiome and the gut microbiome

The soil microbiome and its functions

Soil hosts an incredible diversity of microorganisms, i.e. fungi, bacteria and algae. Soil is probably the most species-rich ecosystem on earth. The entity of microorganisms in a particular environment is called the microbiome. The **soil microbiome is essential for soil functioning.** Bacteria and fungi are the key drivers of nutrient cycling, decomposition, and stabilization of soil organic matter (SOM). Microorganisms thus feed the plants, but also protect them from diseases as well as abiotic stress factors. Biodiversity is crucial for maintaining these processes, since higher variety also means a higher chance for plants to get proper nutrition and respond to stressors, especially in a changing environment.

A substantial fraction of soil microbes is also able to colonize the plant, in the rhizosphere (i.e. soil around plant roots), in the phyllosphere (i.e. on stem and leaf surfaces) and in the endosphere (i.e. in inner plant organs, such as leaves, fruits and seeds). These plant-associated and plant-internal microorganisms support plant health in many ways, e.g. by increasing their resistance to various stress factors, including pathogens. Plant-associated soil microorganisms, in particular root symbionts can, however, also directly increase the nutritional value of crops, e.g. by enhancing the content of vitamins, mineral nutrients, and antioxidants (see chapter 3). The **soil microbiome has been drastically changed** in the last decades, mainly due to intensive agriculture, but also due to other soil threatening processes that were already described in the chapters above. In agriculture, the application of mineral fertilizers and pesticides as well as the cultivation of monocultures and reduced crop rotation has led to a reduction in microbial diversity. Consequently, also plant quality and health has decreased (see chapter 3). It is likely that soil degradation processes and climate change will have further negative impacts on soil microbial diversity.

Connections between the soil microbiome and the human gut microbiome

In recent years it has become clear that **microorganisms connect the different components in terrestrial ecosystems,** such as soil, plants, animals, and humans. Recent research has shown that **soils, plants, and the human gut share many microbial species.** By consumption of plants, but also of plant-associated soil particles and in specific cases even the direct ingestion of soil particles, either by purpose (also called geophagy) or accidentally (e.g. children playing on the ground or the contact with faeces (earlier also called “night soil”)), soil microbes enter the human body and become establish there, e.g. on the skin, in the mouth or in the gut. The latter contains the largest abundance and diversity of microbes in the human body.

In analogy to the soil microbiome, the microorganisms in the human gut comprise the gut microbiome. The extent of the **human microbiome** is impressive: there are about 10 times more bacterial cells than human cells, and the total bacterial genome exceeds the human genome by a factor of >100. The gut microbiome starts to develop before birth and becomes fully established 2-3 years later. The inoculation of the gut by microbes is boosted during birth and continues afterwards by food and soil particle consumption. Later, the individual diet predominately shapes the gut microbiome. Studies on humans have shown that individual eating habits are more important for gut health than genetic background. In general, food that is rich in fibers and carbohydrates will positively influence the gut microbial diversity and feed many beneficial gut microorganisms.

As with soil, the gut microbiome is also important in **nutrient production and cycling.** Many substances cannot be broken down by the human body, thus the fermentation by microbial cells is essential to support the human body with essential compounds. Moreover, gut microbial diversity is linked to modulating the im-

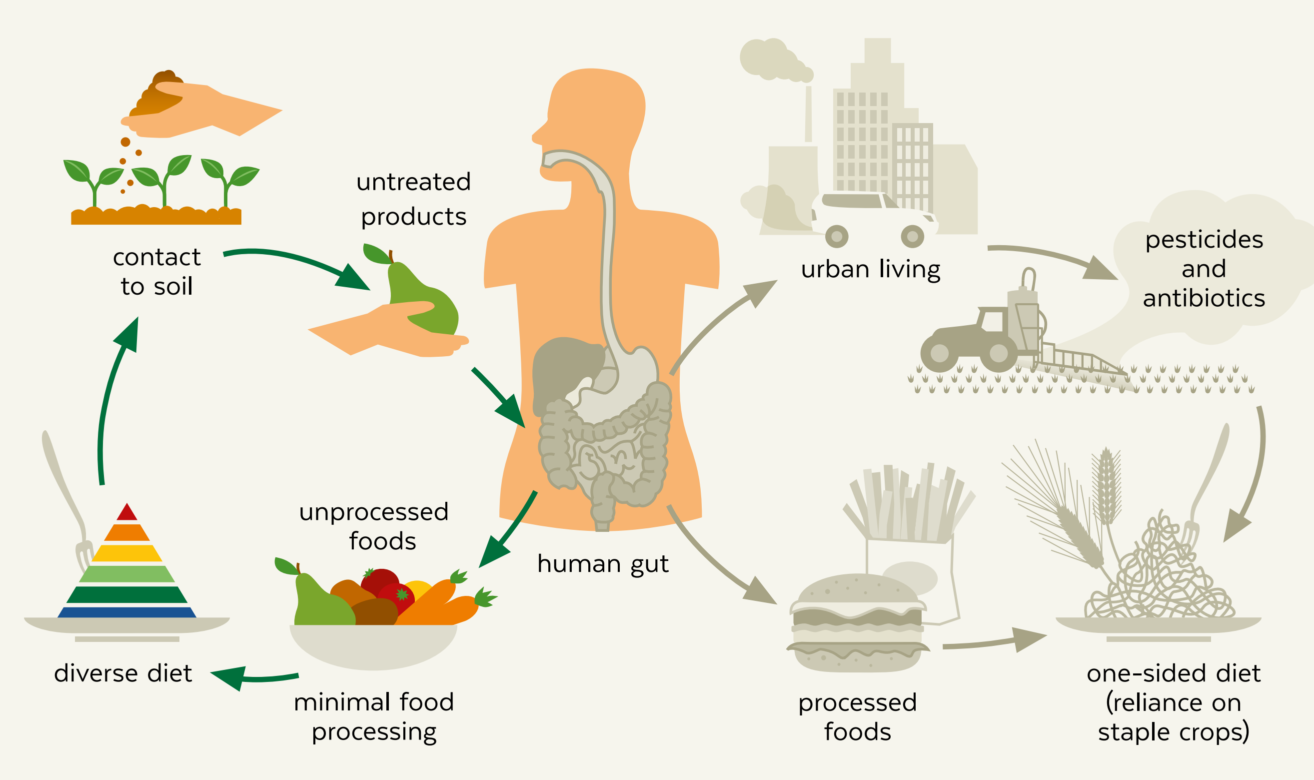

Figure 5: Gut health

mune system and to the occurrence of diseases such as diabetes, obesity, cardiovascular and even neurological diseases. Like for soil, the health of the human body is thus directly depending on the microbial diversity in the gut. Earlier human populations have always been in close contact with soil due to their activities in agriculture and animal husbandry. By **losing contact with soil,** but also with untreated plant products, the gut microbiome of urban citizens has changed and has become less diverse. Undoubtedly, improved hygiene, the use of antibiotics and modern agricultural practices have led to an enormous reduction of human disease burden and mortality. Nevertheless, having direct contact with a microbe-rich environment is an important factor in protecting humans against allergies and autoimmune diseases.

Overall, it has been shown that the biodiversity of the gut microbiome has become reduced under the influence of the so-called **Western lifestyle,** which is based on intensive agriculture and industrialized food processing.[50] However, **locally produced food derived from sustainable farming** may be a way to integrate the lifestyle of earlier generations into our modern world. This would not only support the development of an improved gut microbiome, but also improve microbial diversity in soil and thus support the ecosystem functions of soil in an overall improved terrestrial environment.[51]

Soil is, however, not only hosting beneficial microorganisms, but is also a reservoir of **pathogens.** Soil bacteria such as *Bacillus anthracis,* which is causing anthrax, a potentially deadly disease for animals and humans, is globally widespread and may cause infections by uptake from soil or from the soil-plant-food continuum. The occurrence of such pathogenic bacteria and the risk of getting infected depends on the microbial diversity in soil. It has been shown that high microbial diversity reduces the risk of infectious diseases from soil-borne pathogens. This is relevant for both human and plant pathogens.

Climate change poses a threat to soil, as already highlighted above. These effects include also changes in the soil microbiome, which in turn will also have an impact on the human microbiome. A recent study has shown that rare microorganisms are more strongly affected than the dominating microbial species.[52] This is of critical importance, since some of these rare microorganisms drive ecosystem functions of soil.

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[50] **Hirt, H.** (2020) Healthy soils for healthy plants for healthy humans. EMBO Reports 21.

[51] **Singh, B.K.** et al. (2023) Soil microbiomes must be explicitly included in One Health policy. Nat Microbiol 8, 1367–1372.

[52] **Zhou, Z.** et al. (2020) Meta-analysis of the impacts of global change factors on soil microbial diversity and functionality. Nat. Commun. 11, 1–10.

5

Implications for soil management

Several **soil management strategies influence soil health** and with that the soil microbiome, water quality and food quality. There is great potential to reduce, reverse or slow down soil degradation processes and support and maintain soil health. Some of those management measures and potentials are explored in this chapter. It focuses on sectors which closely interact with and influence soil – namely agriculture, forestry, and urbanization as well as contaminated sites.

Agricultural measures for soil health

Agriculture is undoubtedly one of the main human-made interventions on soil. No other sector depends as much on soil health as agriculture does, with wide-ranging implications for food security, global food trading and human health. Apart from that, the Common Agricultural Policy (CAP) amounts to around 33% of the EU budget, making agriculture in the EU an important financial sector. Its environmental and financial stability strongly depend on the sustainable management of the resource soil – with its degradation and depletion the EU risks an agriculture which is unable to sustain food security, environmental safety and economic feasibility. Many soil-related ecosystem services depend on its health – thus, soil health should be the central element of the CAP.

The following **soil health principles**[53] are recommended to be included as guidelines for EU-wide agriculture:

1. **keep soils covered as much as possible**
2. **minimize soil disturbance**
3. **grow a diversity of plants**
4. **continuously maintain living roots throughout the year**
5. **integrate livestock into agroecosystem**

In the following, specific management options for intensively and extensively used land are presented – all in line with the above-mentioned soil health principles. In short, management practices should be oriented towards **building, maintaining, and supporting a healthy soil microbiome.**[54, 55] Increasing soil organic matter (SOM) is one of the most important measures towards that goal, because the soil microbiome feeds on organic matter. SOM can be brought into the agricultural system via organic fertilization with manure or nitrogen-fixing crops. **Minimal and targeted pesticide application** helps the microbiome thrive and the plant to develop its own defense mechanisms. **Reduced or no tillage** maintains an intact soil structure and improves water infiltration and availability. It also enables earthworms to form stable clay-humus-complexes which are crucial for long-term soil fertility. **Covering the ground** as much as possible also improves soil structure, reduces erosion, and brings organic matter into the soil. Cover crops, catch crops and organic mulching are management options for covering the ground and simultaneously feeding the soil microbiome by introducing organic matter into the system.

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[53] **Guo, M.** (2021) Soil Health Assessment and Management: Recent Development in Science and Practices. Soil Systems 5.4.

[54] **Bertola, M.** et al. (2021)

[55] **Montgomery, D.R.** and **Biklé, A.** (2021)

Catalogue of measures for soil health in farming systems

Soil health highly benefits from switching mineral fertilizers to **organic fertilizers and amending soil organic matter** (SOM).[56] Examples for organic fertilizers are compost, mulch, manure, biochar or planting legumes. Some of them cover the soil (like mulch), relating to principle 1, others include livestock products (like manure), relating to principle 5. Organic fertilizers improve soil structure via aggregation, support water uptake and holding capacity, improve microbial activity and nutrient cycling and can suppress diseases. However, careful management is required for reducing the possibility of nutrient leaching. Most importantly, nutrient releases from organic fertilizers via mineralization need to be synchronized with nutrient demands of crops.[57]

Crop rotation is another measure supporting soil health.[58] It relates to principle 3 by diversifying crops temporally. This practice is known for aiding disease control by various mechanisms: it breaks the disease cycle so that the host plant is not always present, and exudates of one plant might fight pathogens of other plants. Under crop rotation, plant residues and roots also add organic matter to the soil. It helps nutrient balancing since different crops extract nutrients to a varying extent and can also benefit each other – e.g. growing legumes previously to nitrogen-demanding plants supplies the latter with nitrogen and thus reduces fertilization needs.

Cover crops and intercropping are other central measures for soil health in farming.[59] They relate to principles 1, 3 and 4 by adding soil coverage, plant diversity and living roots to the agroecosystem. Cover and inter crops – like the names suggest – cover soils with their leaves and thus prevent erosion and slurry seal coating. Their roots provide structural stability, keep the soil well aerated and improve water uptake and holding capacity. On top of that, the roots and plant residues bring organic matter into the system and support nutrient cycling via microbial activity. Intercrops can strengthen main crops, though a careful selection and combination of plants is needed here to maximize benefits and reduce adverse effects – e.g. combining grasses and legumes reduces the probability of nutrient leaching.

One best-practice example for a mixed cropping system is the lighthouse farm ERF BV located in the Netherlands (Picture 1). Their organic farming system works with strip cropping, a way of diversifying agriculture on a large scale.[60]

Conservation tillage is another backbone for soil health in agriculture.[61] It supports principles 2 and 4 by reducing the amount of physical disturbance (tillage, ploughing) and simultaneously keeping roots in the soil (even after the crop itself is harvested). Conservation tillage can include measures such as no tillage, strip tillage, ridge tillage, etc. Soil health effects of reduced tillage often originate from benefits related to continuous rooting of the soil. This means that reduced tillage should be implemented in combination with an adapted crop rotation, which includes cover crops, catch crops and optimized crop rotation. This way, it preserves the soil's structure and aggregate stability, thus reduces erosion risks, and improves water uptake and storage capacities for water. This management type conserves organic matter at least in top soil and can lead to a steadier release of nutrients from organic matter. In contrast, conventional ploughing can break up soil aggregates, exposing formerly protected organic carbon to the decomposition by microorganisms and the subsequent release of CO_2.[62] However, as with other measures, conservation tillage requires careful embedding into other measures, which means that alternatives for weed control (such as mulching, intercropping and crop rotation) must be implemented. Furthermore, combining conservation tillage with mineral fertilizer application (or other water-soluble fertilizers) on uncovered soil might pose the risk of nutrient losses by surface-runoff if the fertilizer is not incorporated into the soil. Overall, it is the combined application of measures that determines the efficiency in increasing the soil organic carbon, highlighting the need for a holistic and integrated management approach.

There is an ongoing debate whether no-till systems require heavy input of herbicides to control weed pressure on crops. However, if management is designed in depth, herbicide use as well as tillage can be redu-

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[56] **Tahat, M.M.** (2020) Soil Health and Sustainable Agriculture, Sustainability 12.

[57] **Rayne, N.** and **Aula, L.** (2020) Livestock Manure and the Impacts on Soil Health: A Review. Soil Systems 4.4

[58] **Yang, T.** et al. (2020) Cropping Systems in Agriculture and Their Impact on Soil Health-A Review. Global Ecology and Conservation 23

[59] **Bertola, M.** et al. (2021)

[60] *https://www.lighthousefarmnetwork.com/lighthouse-farms/erf. Accessed 11/10/2023.*

[61] **Clemensen, A.K** et al. (2020)

[62] **Tiefenbacher, A.** et al. (2021) Optimizing Carbon Sequestration in Croplands: A Synthesis. Agronomy 11, 882.

ced drastically. Crop rotation and continuous covering and rooting of soil seem to be two major elements towards no-till herbicide-free systems. In addition, a step-by-step tillage reduction can gradually shift weed communities, making a weed-specific management possible. To reach no-tillage herbicide-free systems, new approaches beyond currently known practices are needed, and more research is currently underway.[63]

Using **biological plant protection** instead of conventional pesticides supports soil health too.[64] It keeps the microbiome abundant and diverse and activates the plants' own defence mechanisms. That, in turn, produces plant secondary compounds and elevates the nutritional value of food. Not only soil, but also water benefits from switching from conventional to biological plant protection. As included in the Soil Strategy 2030, water bodies should reach a good ecological and chemical status by 2050 – supporting the use of biological plant protection serves as measure for reaching that goal. The Soil Strategy 2030 already includes the revision of the guidelines for sustainable use of pesticides, and it should also include guidelines for biological plant protection.

More variety in the **choice of cultivars** can further assist soil health and the resilience of the whole agroecosystem.[65] Certain cultivars might be more nutritious and / or more resistant to pathogens and environmental stress then others. This reduces the need for agrochemicals and irrigation and thus keeps the soil healthier. Diversification also relates to principle 3 of soil health.

Agroforestry is one key concept supporting not only soil health, but also resilient and self-sufficient agroecosystems and heterogeneous landscapes offering high biodiversity.[66, 67] The concept includes intensively as well as extensively used systems and mainly focuses on combining woody perennials (trees and shrubs) with annual crops in varying levels of complexity. To a certain degree, this system mimics nature and uses naturally occurring processes when trees and shrubs are present. It relates to principles 3 and 4 by diversifying the agrarian landscape and maintaining the living roots of perennials in the ground over several years to decades. Agroforestry practices show various benefits: they prevent overall soil degradation and offer many microclimatic advantages. This is mainly mitigated via the evapotranspiration and cooling effect of woody perennials, leading to a better water availability for crops. Trees and shrubs control erosion by a) allowing for a slower water infiltration via leaf interception and b) reducing wind speeds. Their roots serve as a safety net for nutrient leaching and make nutrients and water available in upper soil layers. Plant and root residues (e.g. leaf litterfall) add organic matter to the system, assisting the soil microbiome. Agroforestry combines many benefits into a simple and effective approach. A well-designed agroforestry system provides not only a higher resilience of the agroecosystem but also supports biodiversity, local and indigenous knowledge and community welfare. The EU is recommended to work together with its member states for reducing legal obstacles for the national and international recognition and support of agroforestry systems.

A Best-Practice-Example for agroforestry in a regenerative agricultural system is the lighthouse farm La Junquera in Spain.[68] The applied system combines several measures like conservation tillage, mulching, water harvesting methods and including woody perennials in the landscape.

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[63] **Colbach, N.** and **Cordeau, S.** (2022) Are No-Till Herbicide-Free Systems Possible? A Simulation Study. Front. Agron. 4.

[64] **Mou, B.** (2005)

[65] **Sarkar, D.** et al. (2021) Organic Interventions Conferring Stress Tolerance and Crop Quality in Agroecosystems during the United Nations Decade on Ecosystem Restoration. Land Degradation & Development 32.17, 4797–4816.

[66] **Fahad, S.** et al. (2022) Agroforestry Systems for Soil Health Improvement and Maintenance. Sustainability, 14.22.

[67] **Gupta, V.P.** (2020) Role of agroforestry in soil conservation and soil health management: A review. J Pharmacogn Phytochem 9, 555-558, and references therein.

[68] *https://www.lighthousefarmnetwork.com/lighthouse-farms/la-junquera. Accessed 11/10/2023.*

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Pictures 1 and 2:
Agroforestry systems on the Grand Farm in Austria

Another agroforestry example of the Grand Farm in Austria is shown in pictures 1 and 2.

Apart from those management measures, several other interventions like **inoculating soil with beneficial microorganisms** like rhizobacteria and mycorrhiza can aid soil health. Measures halting soil degradation are essential in every type of agricultural landscape, be it intensive farming or extensive grassland. Those are, e.g. erosion control via **erosion strips** or leaching protection via **buffer strips.**

Especially in dry to arid regions, **water harvesting methods** might be a way to support soil health. Ongoing droughts put pressure on soils and crops, thus retaining water in the landscape is crucial – moreover, it reduces the need for irrigation and risks of erosion.

Water harvesting methods catch and collect water that enters the ground and can range from highly technical to simple, small-scale interventions.[69] Water harvesting is especially important and especially effective on slopes, where water tends to run-off in a distinct direction. Water can be caught using swales, dams and micro-catchments. In the case of the Keyline Design, dams are built parallel to the slopes contour lines. Rainwater is caught in front of the dams – usually stabilized by plants – from where on it can slowly infiltrate into the soil. Little ponds and natural depressions can serve as water harvesting facilities, too. On a smaller scale, micro-catchments like planting pits, vegetation strips, contour bunds and ridges can catch water close to the root zones of, e.g. trees – this way, water enters the local water cycle between soil – plants – atmosphere rather than being washed away into rivers. Fog nets are another opportunity for retaining water in the landscape, especially where precipitation via rain is very low. Water harvesting methods are currently gaining attention, since they seem to be promising climate change

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[69] **Mekdaschi Studer, R.** and **Liniger, H.** (2013) Water Harvesting: Guidelines to Good Practice. Centre for Development and Environment (CDE), The International Fund for Agricultural Development (IFAD), Rome.

Copyright: with curtesy of Alfred Grand, Grand Farms

adaptation tools: with more extreme droughts and heavy rainfall events risks of surface runoff increase, meaning that less water will be taken up and stored in the ground. Irregular rainfall events (in frequency and intensity) can be challenging for agriculture – water harvesting methods potentially can mitigate those adverse effects by catching and storing water where it is needed.[70]

Catalogue of measures for soil health in grassland systems

Grassland suffers from different soil degradation pressures than arable land. Primarily, measures contributing to soil health should focus on avoiding over-grazing and over-mowing. Grazing can aid soil health via enhanced nutrient cycling, allocation of carbon in root biomass and high plant biodiversity. However, if becoming too intensive, grazing and mowing can also contribute to soil degradation.[70] A soil health promoting type of management can be reached via **rotational grazing and mowing,** which stores soil organic matter (SOM) and carbon in the ground and avoids compaction via ruminants and / or heavy machinery. **Timing grazing and mowing** adequately, i.e. no grazing and mowing on wet soil, is another key component for avoiding compaction and grassland degradation. **Increasing plant diversity** further aids soil health and provides habitat diversity for grassland species to thrive. Overall, **extensification** of grassland use is the ultimate measure for increasing soil health.

In some regions, this might also include **rewetting** measures in the landscape – drainage systems have degraded wetlands and organic soils that developed in the presence of excess moisture became a source of greenhouse gas emissions. With respect to climate change and biodiversity loss, rewetting near-natural

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[70] **McTavish M.J.** et al. (2021) Chapter 4 - Sustainable Management of Grassland Soils. In: Stanturf, J.A. and Callaham M.A (2021) (Ed.), Academic Press, 95-124.

and degraded peatlands and removing drainages can restore these unique soils with their outstanding carbon storage potential, contribute to improved water retention and create valuable habitats. Rewetting requires careful planning and execution to avoid adverse effects on soil and environment. Depending on the wetland type (bogs, fens, mires) and the hydrological situation of the site different management concepts are required.[71] The EU should continue rewetting programmes like LIFE Peat Restore and could further aid rewetting by assisting the identification of previously drained landscapes and creating of rewetting action plans. Moreover, selected soils that developed in the presence of excess water but were drained and used for agriculture or forestry can be restored (temporarily) by raising the water table and establishing nature-compatible cultivation, i.e. paludiculture. This relatively new approach for peat-preserving use of cultivated wetlands should be emphasized by supporting initiatives to identify suitable locations, technically realize restorations and establish sustainable production of wetland crops as well as the commercialization of the resulting products.[72]

Policy suggestions for soil health in agriculture

As mentioned above, the Common Agricultural Policy (CAP) and soil health strategy should **include soil health principles** as a guidance for specific measures and processes towards soil health goals. For all agricultural soil interventions, independently of intensity, a **holistic and integrated design of measures** is required, where measures work together to create synergies and keep labour intensity as low as possible. The design should be carried out on a local scale, in close cooperation with **local soil health experts** who assist farmers in designing and implementing their locally adapted management concept. The Soil Strategy 2030 already suggests a free soil testing opportunity for each landowner and could be broadened to include a free first consultation on soil health management measures by local soil health experts. A regional, national, and international soil health expert network could aid knowledge transfer and the representation of best-practice examples.

As mentioned above, a framework for EU-wide **recognition and support of agroforestry systems and rewetting schemes** should be a further step in reducing soil degradation.

Soil health does not only depend on current but also on past soil management (soil management legacies) and the nature of soils requires up to several decades for remediation – thus, all measures and their evaluations should consider **long-term effectiveness and time lags.**

The **Annex I** of the proposal for a Soil Monitoring Law includes elaborated soil descriptors for healthy soil condition, land take and soil sealing. Additional descriptors could include soil aggregate stability, nutrient leaching (as extension of nutrient excess), amount of agrochemical residues (pesticides, herbicides, antibiotics) as well as micro- and nanoplastic residues. Furthermore, the Soil Health Principles of **Annex III** are already elaborated but could be expanded by principles 4 (maintaining living roots throughout the year) and principle 5 (integrating livestock and livestock products) which are not specifically mentioned.

To implement some of the above-mentioned measures in farming, the EU should **widen the already existing conditionality of the CAP's first pillar:** the percentage of area required for landscape elements could be raised, initiating agroforestry elements. Further, crop rotation is already one of the conditionalities – soil coverage should also be one of them. Soils should only be allowed to be uncovered for a limited amount of time during the year, incentivising cover crops and mulching. Another conditionality of the CAPs first pillar could be a mandatory application of a certain amount of organic matter (in the form of compost, mulch, manure, legumes, biochar, harvest residues) per year, accompanied by best practice guidance to conserve carbon in soil. In the case of biochar, it needs to be considered that although a vast range of positive effects on soil quality and plant growth were observed, some negative effects may also occur.[73] Furthermore, the characteristics of biochar are varying a lot, and the availability is still limited. To avoid soil contamination, it is highly recommended to applied biochar only when it fulfils the quality criteria according to EBC.[74]

[71] **Joosten, H.** (2022), Global Guidelines for Peatland Rewetting and Restoration. Ramsar Technical Report No. 11. Gland, Switzerland: Secretariat of the Convention on Wetlands.

[72] **Geitner, C.** et al. (2019): Tiroler Moore unter Landwirtschaft - Datenlage und Flächenanteile, Nutzungsgeschichte und Zukunftsperspektiven, diskutiert am Beispiel des Viller Moors bei Innsbruck. In: Innsbrucker Geographische Gesellschaft (ed.). Innsbrucker Jahresbericht 2018 - 2019. Innsbruck: Innsbrucker Geographische Gesellschaft, 30 - 50.

[73] **Verheijen, F.** et al. (2010) Biochar application to soils. *https://publications.jrc.ec.europa.eu/repository/bitstream/JRC55799/jrc_biochar_soils.pdf.* Accessed 12/10/2023.

[74] The European Biochar Certificate (EBC) (2023) *https://www.european-biochar.org/en/ct/1.* Accessed 12/10/2023.

It is not sufficient to provide ambitious targets for soil health – realistic milestones should not only include the goal but also **nudge a *process*** of reaching them and **enforce *consequences*** when goals are not reached. Processes of reaching healthier soils not only include land-based measures like the ones presented above. In fact, it seems unrealistic to establish healthy soils solely by changing practices on the land. Wider-ranging, **systemic changes** like the transition of our food system, including dietary shifts and food waste avoidance are inevitable for long-term soil health. Concepts oriented towards those holistic approaches include agroecology, regenerative agriculture, restoration agriculture, carbon farming and agroforestry.

Take-home messages for soil health in agriculture:

Policy and management of agricultural sites should focus on mimicking natural processes (e.g. integration of woody species, continuous coverage of soil), storing organic matter and carbon in the ground and applying locally adapted integrated management concepts elaborated with local soil health experts.

Forestry measures for soil health

Catalogue of measures in the forestry sector

Apart from agriculture, forestry also highly intervenes with soil and is equally dependent on soil health. The concept of sustainability originates from forestry, since timber production and related ecosystem services happen on larger time scales than, e.g. agriculture – the effects of unsustainable forest management can manifest during one rotation period already, making a forestry system especially vulnerable. The EU Soil Strategy 2030 does not sufficiently highlight the importance of soil-related forestry pressures: climate change and biodiversity loss are two highly important focus points which are interlinked with forest soils (e.g. via soil carbon storage and soil fauna diversity). However, they result from a combination of underlying interventions and mismanagement, partly over several decades. Policy should focus on those drivers and implement tangible guidelines for sustainable management of forest soils. Some examples are explored in the following.

Changing from forest monocultures to mixed cultures is one major step in supporting forest soil health.[75] In many temperate regions of Europe this also means switching from coniferous plantations to broadleaf species. Growing a mixed culture supports soil organic matter and microbial diversity, e.g. via diverse litter input and root exudates. Coniferous and broadleaf species also tend to store carbon differently in the soil: whilst the former increase carbon stocks in the forest floor, the latter increase carbon stocks in the mineral soil.[76] Thus, mixing both species offers diverse use of carbon pools. A broadleaf foliage leads to higher interception and thus slower water interception and lower erosion risks. It also provides the soil with moisture, leading to a better water balance than in soils with dry coniferous needle litter. A mixed culture is less prone to large-scale pathogen infestation like the recent bark beetle outbreaks – in a diverse forest, some species can buffer and replace lost ecosystem functions of other species affected by the pathogen. This prevents large forest areas from being destroyed by one single beetle species (e.g. as it was the case for Harz National Park in Germany). Large-scale destruction of forests by pathogens has similar consequences as clear-cutting regarding risks of erosion, nutrient leaching, and soil organic matter degradation. When mixing species, not only the number of species should be considered, but also the species identity and its ability to cope with current and future climatic and environmental pressures.

Single tree harvesting instead of clear-cutting is another central step in supporting soil health.[77] During and after clear-cutting, forests sites are the most vulnerable. Single tree harvesting reduces risks of wind and water erosion compared to clear cuts, because the soil is still vegetated and thus protected. It also reduces the risk for nutrient leaching, because – unlike for clear-cuts – living roots still take up nutrients and nutrient cycling is of slow to moderate pace. This preserves soil organic carbon in the soil rather than quickly decomposing it into atmospheric CO_2. Furthermore, during clear-cuts, a large area is heavily affected by soil compaction. Single tree harvesting avoids large-scale compaction and, if designed well, reduces the frequency and magnitude of compaction.

[75] **Liu, C.L.C.** et al. (2018) Mixed-Species versus Monocultures in Plantation Forestry: Development, Benefits, Ecosystem Services and Perspectives for the Future. Global Ecology and Conservation 15.

[76] **Mayer, M.** et al. (2020) Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. Forest Ecology and Management 466.

[77] **Worrell, R.** and **Hampson, A.** (1997) The Influence of Some Forest Operations on the Sustainable Management of Forest Soils— a Review. Forestry: An International Journal of Forest Research 70.1, 61–85.

Optimizing harvesting methods[78] – apart from single tree harvest vs. clear-cut – also highly influences soil health. The main effect of harvesting is soil compaction – sometimes irreversibly – which should be kept to a minimum. Reducing the number of load passes or minimizing trail slopes can assist that. Additionally, applying mulch after skidding can prevent erosion losses. Using animals for harvesting instead of heavy machinery is known to be an ecologically friendly, soil conserving harvesting method. **Optimizing harvesting and transportation routes** is also key for keeping as much soil as possible undisturbed and for preventing soil erosion and sealing.

The pictures 3 and 4 show examples for optimized, soil conserving harvesting methods: small-scale route development for drag routes (picture 3) and a slope harvester with suspension ropes (picture 4).

If interventions are not avoidable, they should have **proper timing.**[79] Using heavy machinery on wet forest soil poses a much greater risk for compaction than on frozen or dryer soil. Apart from that, **increasing rotational lengths**[79] creates less frequent interventions and thus reduces risks for erosion, leaching and compaction. Longer rotation periods can be reached by planting less productive species which require more time for biomass production. When reducing the intervention frequency, soils have more time for recovery – resulting in a healthier, more fertile soil.

Retaining deadwood, leaf foliage and branches in forests is crucial for long-term soil health and soil fertility. It feeds soil organic matter to the soil microbiome, thus aids nutrient cycling and provides a healthy, well aerated soil structure with a high water uptake capacity. Deadwood is especially important for soil fungi to thrive, which live in close association with trees and are essential for a healthy forest stand.

Preventing and managing forest fires might be another important consideration for soil health in fire-prone areas.[80] Like post clear-cuts, post fire areas are especially vulnerable to erosion, nutrient leaching and carbon loss. Thus, prevention measures avoid soil degradation and assist soil health. Forest fire prevention measures like thinning and prescribed burning might interfere with and contradict other soil health measures (e.g. retaining deadwood). In those cases, a locally adapted analysis of risks and pressures should be carried out – which then points towards the most urgent measures to be taken.

Lastly, **extensivation and rewetting** support forest soil health. Extensivation can look like putting forests out of use or reducing interventions to mimic natural disturbances. Rewetting is – similarly to rewetting of agricultural land – challenging and requires careful design and management. However, it can offer great benefits for soil health, climate action and forest biodiversity.[81] Many European soils – similarly to agricultural landscapes – have been intensely drained, which degraded valuable peat soils and made flooded forests (e.g. swamp or alluvial forests) highly threatened. Rewetting offers a re-establishment of unique forest soils with unique forest species and a high carbon storage potential.

Policy suggestions for soil health in forestry

Unlike for agriculture, the EU does not have a common forest policy – forestry is largely a national competence. These juristic differences between agriculture and forestry make binding regulations and legislation for soil health in forests more challenging. Nevertheless, the EU offers a Forest Strategy 2030 (similarly to the Soil Strategy 2030). This is crucial since forestry is one of the main land use types in the EU, shortly after agriculture, and thus highly influences soil quality in the EU member states. The **"Guidelines on Closer-to-Nature Forest Management"**[82] collect wide-ranging measures on sustainable forestry, including some of the above-mentioned measures (establishing mixed and continuous-cover stands of diverse age, deadwood reservoirs and protected habitats, etc.). However, specific instruments on implementing those guidelines are – up until now – mainly voluntary and could be expanded to ensure a widespread application.

[78] **Picchio, R.** et al. (2020) How and How Much, Do Harvesting Activities Affect Forest Soil, Regeneration and Stands?. Current Forestry Reports 6.2, 115–28.

[79] **Worrell, R.** and **Hampson, A.** (1997)

[80] **Agbeshie, A.A.** et al. (2022) A Review of the Effects of Forest Fire on Soil Properties. Journal of Forestry Research, 33.5, 1419–41.

[81] **Escobar, D.** et al. (2022) Back to the Future: Restoring Northern Drained Forested Peatlands for Climate Change Mitigation. Frontiers in Environmental Science 10.

[82] European Commission (2023) Guidelines on Closer-to-Nature Forest Management *https://environment.ec.europa.eu/system/files/2023-07/SWD_2023_284_F1_STAFF_WORKING_PAPER_EN_V2_P1_2864149.PDF. Accessed 10/10/2023.*

Picture 3: Optimized small-scale development of drag routes for tree harvesting

Copyright: with curtesy of the BFW Austria

Picture 4: Slope harvester with suspension ropes for optimized harvesting in mountain areas

Copyright: with curtesy of the Austrian Research Centre for Forests (BFW), Austria

Generally, **clear-cuts and whole-tree harvesting should be prohibited** on all sites. This would be a simple, yet profound measure which could reduce common problems of erosion, nutrient leaching, compaction and simultaneously halt ecosystem degradation in forests and promote carbon accumulation.

Compaction is one of the major drivers of soil degradation in forest ecosystems and thus needs to be tackled via policy. It mainly occurs from using heavy machinery on moist soil which is more susceptible to compaction than a dry soil. Compaction causes lower water uptake capacities and thus more surface runoff and erosion. One possible instrument could be a **threshold value of soil moisture** from which on forest soils are not allowed to be passed anymore.

Certainly, diversification of tree species is a key factor in supporting forest soil health. Not only does it enhance soil microbial communities, provide diverse organic matter and ameliorate the local water balance. Diversification also increases a forest's resilience to disturbances like pathogen attack or wildfires. Especially in the context of climate change-induced pressures, this is of major importance. However, stand diversification is not as straight forward as it sounds – local circumstances like climatic and soil conditions as well as local pressures from forest fires, pathogens, windthrow, erosion, etc. create a high diversity of situations which require diverse local solutions. For example, in northern areas like Scandinavia the possible species diversity is limited compared to temperate regions – or places like the Mediterraneans experience different pressures from forest fires than central Europe does. Thus, a local assessment of diversification possibilities should be established. Based on local conditions and risks, a **diversification index** could be elaborated – indicating the possible number of species, their distribution and which species could be suitable for the respective location.

Generally, **financial incentives** should enforce forest conversions in accordance with the Closer-to-Nature Forestry Guidelines – a network of practitioners could ensure wider-ranging landscape benefits above the stand level. Forests are Europe-wide ecosystems, and even though a coherent European policy is missing, the EU should still enable Member States to network and coordinate their efforts for large-scale benefits.

Urban and contaminated soil management measures for soil health

Catalogue of measures in the urban and waste management context

Urban and industrial areas take up another large part of soil-related human interventions. Soil policy in this sector should focus on increasing surface permeability, amount of vegetated area and remediation of contaminated sites.

Soil sealing (see chapter 1) is one of the main soil degradation processes in Europe and especially prevalent in urban areas. Soil sealing leads to a complete loss of soil permeability – meaning that water cannot infiltrate the ground anymore but is washed away on the surface (surface runoff). In urban areas the water ends up in sewage systems. With increasing intensity of rainfall events as a result of climate change, the amount of water and thus the pressure on sewage systems is rising. Consequently, sewage systems might get overloaded, leading to the potential spill of excess water flows into streams (e.g. rivers or creeks), which may ultimately cause the flooding of large areas and thus severe damaging of infrastructure and risk human livelihoods in affected areas. Sealing is one of the main reasons for flood risks in highly populated areas. Moreover, surface runoff instead of infiltration limits groundwater recharge, possibly increasing difficulties in water supply.

The **concept of "Sponge Cities"** addresses the importance of soils in the water and temperature balance of urban areas. It is based on the capacity of soils to take up and store water in huge well-designed belowground substrates, thus preventing floods by efficient water infiltration and at the same time also water shortages by optimized water storage.

Surface permeability needs to be protected and maintained where it is already or still present. One instrument could be regulations on a **mandatory percentage of permeable surface** that needs to be maintained in every construction project.[83] E.g. regulations on the mandatory use of grass-gravel covers – low in costs and maintenance – instead of concrete for parking lots could be put into place.

Soils should not only be un-sealed but also revegetated. **Vegetation on soil** plays a crucial role in urban areas. It allows more efficient water infiltration through leaf interception, higher porosity through roots and organic matter and a cooling effect on the surface air temperature. Thus, vegetation helps to take up and retain water in cities and is key in reducing heat is-

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[83] C40 Cities Climate Leadership Group, Inc. (2023) Flooding: How to increase your city's permeability *https://www.c40knowledgehub.org/s/article/Flooding-How-to-increase-your-city-s-permeability?language=en_US. Accessed 05/10/2023.*

land effects. Regulations on **mandatory percentage of vegetated soils** could be another instrument for soil health in urban contexts.

For already existing infrastructure permeability should be increased as much as possible. Blue and green infrastructure (water bodies, vegetation elements) are central to **Nature-based Solutions (NbS),** which are some of the cheapest flood and heat protection measures. They require little technological and constructional effort and little maintenance and help to decrease the severity of flood events and potential damages. NbS can increase permeability of already existing infrastructure, e.g. patches of permeable soil with vegetation alongside sealed areas like roads. Some options are: bioswales, natural retention ponds, vegetation filter strips, drainage systems to nearby vegetation root zone, rain gardens, kerb openings and roadside lateral inlets.[84] Those small-scale solutions take up and store stormwater locally, filter it before it reaches the groundwater and stop possible erosion of sediments. A mosaic of small-scale NbS can relieve pressures on the sewage system at critical points and contribute to local cooling in public spaces. Several European cities have already established NbS, e.g. London in its "Sustainable Drainage System" and Copenhagen in its "Cloudburst Management Plan", and some Best-Practice Examples are highlighted in the pictures below.

Another measure for increasing soil health in cities is the **transformation of unused infrastructure** – e.g. old railways or brownfields – **into vegetated areas.** This not only aids flood protection and reduces heat islands but also offers recreational benefits for local communities and habitats for biodiversity.

Urban planning should always **include strategic planning** to reduce the amount of sealed area and control urban sprawl to prevent further soil degradation in the first place. Moreover, **flood and heat risk management plans should always consider the role of soils** and not only sewage systems and water bodies. The issue of soil sealing is addressed in the Soil Strategy 2030 – however, specific measures and regulations are missing and should be fostered, amongst them regulations on permeability conservation during construction, investments in NbS innovation, and integrated spatial planning.

Soil contamination is another side effect of urbanization and industrial activities. Soil remediation is one of the central visions of the Soil Strategy 2030 – a new legislative framework on the remediation of contaminated sites is planned. Some of the following measures could be included in the framework.

Bioremediation of contaminated sites is a NbS which can degrade, immobilize and/or extract pollutants and thus ameliorate soil health over time.[85] Remediation and revegetation can be assisted by adding topsoil or mixing available sediments with biosolids (e.g. organic matter from treated sewage sludge) which aid establishment of vegetation.[86]

The application of particular plant species is the basis of phytoremediation approaches.[87] Metal-accumulating plants may even contribute to the removal of metallic pollutants from soil, whereas in phytostabilization or phytomanagement concepts pollutant-tolerant plants are grown for immobilizing the contaminants, thus leading to reduced risk of transfer to the food chain or to the groundwater. **Plant-based approaches** can be effectively assisted by using soil amendments (e.g. lime, iron oxides, biochar) for stabilizing the contaminants. In the case of severely polluted sites, the application of these amendments might even be the basis for establishing a plant cover on otherwise uncovered soil. With this approach, both a chemical immobilization (e.g. by enhancing the binding strength to the soil mineral surfaces) and a physical stabilization (by reducing wind and water erosion processes) of the contaminants is achieved on site.

Organic pollutants, such as pesticides or oil residues, can be degraded by microorganisms. However, polluted soils are often nutrient-poor and suffer from other soil degradation processes. Inoculating the soil with specific microorganisms that can degrade the pollutants can be a starting approach for initiating the degradation process. Plants, however, are important in supporting and boosting the microbial activity: plant roots release a variety of compounds that support the microbial processes. The soil around roots, which is called the rhizosphere, is a hot spot of microbial activities in soil. Thus, it is the synergistic action of microorga-

[84] United States Environmental Protection Agency (2023) Green Streets Handbook. *https://www.epa.gov/sites/default/files/2021-04/documents/green_streets_design_manual_feb_2021_web_res_small_508.pdf. Accessed 05/10/2023.*

[85] **Siebielec, G.** et al. (2010) Handbook for Measures Enhancing Soil Function Performance and Compensating Soil Loss during Urbanization Process. *https://www.researchgate.net/publication/301766106_Handbook_for_measures_enhancing_soil_function_performance_and_compensating_soil_loss_during_urbanization_process. Accessed 10/13/2023.*

[86] **Kumar, K.** and **Hundal, L.K** (2016) Soil in the City: Sustainably Improving Urban Soils. Journal of Environmental Quality 45.1, 2–8.

[87] **Yadav, K.K.** et al. (2018) Mechanistic understanding and holistic approach of phytoremediation: A review on application and future prospects. Ecological Engineering 120,274-298.

nisms and plants that enables an efficient biodegradation process for the removal of organic pollutants.

Bioremediation and phytoremediation approaches are valuable options for sites where technical solutions cannot be applied, either because the costs would exceed the available resources or because the site is not accessible for technical remediation solutions. However, also on accessible sites bioremediation and phytoremediation approaches might be more cost-efficient, although it might have to be considered that biological options might take more time than technical solutions. Moreover, because of their unique conditions, remediated sites can develop into valuable ecosystems with rare species and might even be considered for possible protection.

Pollutants typically occur in different fractions in soil. These fractions differ in their mobility and bioavailability. National legislation is still often considering total concentrations only. With this approach, the environmental risks that are associated with pollutants are often insufficiently considered. However, bioremediation and phytoremediation options often lead to changes primarily in the **bioavailable fraction** of pollutants rather than in the total concentration. This may hinder the application of biological remediation options; therefore, it is highly recommended that national frameworks also integrate methods for assessing the bioavailable pollutant fractions in soil.

Even if no contamination legacy is present, former industrial sites, so-called brownfields, need intervention to establish a restored soil cover, followed by revegetation. **Brownfield revegetation** is already addressed in the Soil Strategy 2030 and supports the re-use of areas (instead of subduing natural land) and reduces the total land use.

Policy suggestions for soil health in urban areas and contaminated land

The concept of **"Sponge Cities" and other Nature-Based Solutions should be included into upcoming soil strategies** as a guiding theme for soils in urban areas. In addition, the EU should offer **Good-Practice-Frameworks of Integrated Urban Planning** and support Member States financially to include soils as a central element of their flood and heat protection concepts. Knowledge hubs and local soil experts could form the backbone of implementing Nature-Based Ssolutions and green infrastructure in cities.

For every construction project, a **mandatory consultation of a local soil health expert** (mentioned above) could be implemented – this instrument could reduce the adverse effects of construction on soil resources. Moreover, a regulation could determine a **mandatory threshold of surface permeability** which must be preserved during and after every construction project – this could even be widened to a mandatory threshold of vegetated surface area for every construction project. Ensuring a mosaic of vegetated areas can reduce heat islands and support water storage locally, allowing for an overall cooling.

Bioremediation and monitoring of contamination should not only be based on pollutant concentrations themselves, but also on bioavailability. More specifically, the aspect "soil contamination" of **Annex I** of the Proposal for a Soil Monitoring Law should include "contaminant bioavailability" as a descriptor, not only the total contaminant concentration.

6

Conclusions

Soil is a complex, precious, and important resource for humans and ultimately for the whole planet. Its unique characteristics, sensitivity, and importance for humans makes it highly relevant to protect. This study shows that soil and its health status influences human health in various ways. Soil health is essentially determining the nutritious quality of the food we eat and the purity of the water we drink, which is fundamental for our wellbeing. On top of that, the quality of soil influences its role in the carbon cycle and thus its capability of mitigating climate change, its possibility to grow forests for renewable biological resources, its ability to metabolize contaminants and its protective role against floods and heat. However, soil is not a stand-alone element but rather a part of a complex entity of soils, plants, animals, microorganisms, air and water – which form a highly complex ecosystem. Managing soil is a crucial part of managing whole ecosystems and ensuring the soil's health and functioning in its specific ecosystem context. Generally, a healthy soil is characterized by a resilient structure and resilient processes, high organic matter content, and high microbial activity and diversity. Those features need to be protected and restored on a large scale.

Undoubtedly, there are many **human-made pressures on soil,** which globally tend to increase in severity and amount. Pressures on soils and drivers of soil degradation are diverse and complex and should be tackled at their root. Those roots lie in the way we humans interact with the land – sealing, contamination, erosion and compaction being the result of anthropogenic activities. Each intervention with soil, be it in agriculture, forestry, or urban development, needs to be planned, guided and regulated carefully.

The EU already implemented many starting points, e.g. the Soil Strategy 2030, the Forest Strategy 2030 and current negotiations on a Soil Monitoring Law. Nevertheless, many soil-related pressures and their adverse effect on soil health continue every day, making actions for soil health more urgent. Ways in which the EU could take actions are:

1. Monitoring local pressures on soils and soil degradation processes

2. Create frameworks for soil health in different sectors, e.g. carbon farming, regenerative or restoration agriculture, agroforestry, agroecology, sustainable forestry, sponge cities, bioremediation, etc - within those frameworks, the EU could offer guidelines for interventions supporting soil health or measures to reduce adverse effects.

3. Where possible, the EU could set regulations on soil health promoting measures – e.g. continuous cover in agriculture, minimum requirements for surface permeability for construction projects – and/or prohibition of practices deteriorating soil health (e.g. clear-cuts in forestry)

Looking at the wider picture, promoting soil health can be combined with strengthening local food systems and self-efficacy of local communities. **Integrated, holistic approaches** could fundamentally change our diets regarding diversity and regionality and could reduce food waste, e.g. through local food networks. Supporting soil health aids carbon storage of many ecosystems, e.g. forests, supports local water cycles, air purification and cooling. On top of that, protecting soil also protects species and habitats and supports biodiversity. It increases the liveability of cities and their resistance against floods and heat. Issues around soil are very urgent, since many people depend on soil functions in the more direct context – as base for food production – but also in the wider contexts of livelihood security and integrity. This is why the EU should **include soil-related issues in all relevant sectors** and **promote soil health protection and support.**

Glossary

Compaction	Process of reducing the pore space and breaking aggregates by e.g. mechanical pressure from using heavy machines on soil
Erosion	Process of soil particles being transported off site by wind or water
Evapotranspiration	The process of water transfer from land via evaporation and transpiration. Evaporation is the change of water in a liquid form to water into a gaseous state. Transpiration is the process of water moving from a plant to the atmosphere via stomata (pores in the leaves)
Leaching	Loss of water-soluble substances from the soil to deeper soil layers or waterbodies via transport of water
Metabolites	Intermediate or end product of metabolism, e.g. of decomposition
Mineralization	Transformation or decomposition of organic matter to its inorganic constituents (e.g. CO_2, N_2, PO_4-), often results in intermediate products (metabolites).
Nutrient cycling	Continuous, dynamic transfer of nutrients from nonliving soil parts to living organisms and back, mitigated by microbial activity and plant growth, ensures nutrient balance and availability in soil
Percolation	Process of water moving through the soils' pore system into deeper layers
Run-off	Water which is not taken up by the soil but instead washed away on the surface
Salinization	Increasing soil salt content due to mismanagement of irrigation and drainage in combination with dry climates
Sealing	Covering of soil by non-permeable material (e.g. concrete), annihilates all soil functions except for carrying infrastructure
Slurry seal coating	Sludging of soil which clogs the pore system and prevents water infiltration, caused by destruction of soil aggregates via raindrops on unvegetated soils
Soil degradation	Loss of soil's capacity to provide its functions, e.g. via reduced soil fertility and structural damage or soil loss
Soil microbiome/ microbial communities	Entity of soil microorganisms which can be seen as the backbone of a healthy, functioning soil and a hub for many important soil processes like nutrient cycling

Soil organic matter	Dark colored part of soil made of decomposed organic material like plant and animal residues, base for soil microbiome and soil fertility
Soil pore system	Ensemble of the spaces between soil particles which host the microbiome and stores and transports water and air
Soil structure	Soil particle arrangement to aggregates, shapes soil characteristics like water storage and uptake capacity, susceptibility to soil erosion
Soil texture	Proportion of sand-, silt- and clay-sized soil particles, shapes soil characteristics like water movement, storage and uptake capacity, and nutrient holding

List of Abbreviations

CAP	Common Agricultural Policy
CO_2	Carbon dioxide
CH_4	Methane
EU	European Union
N_2O	*Nitrous oxide*
NbS	Nature-based Solutions
PSMs	Plant Secondary Metabolites
SOM	Soil organic matter
UN SDGs	United Nations Sustainable Development Goals
WHO	World Health Organization

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