Digging Deeper: Unearthing the Economic Potential of Healthy Soil

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Executive Summary

Healthy soil is fundamental to sustainable agriculture, providing a myriad of ecosystem benefits that extend far beyond crop production. It filters our drinking water, mitigates the negative effects of heavy rains, enhances nutrient cycling, and supports the growth of healthy food. Central to these functions are the soil's organic matter and microbiomes, which collectively enable soil to:

- Increase crops yields by providing higher amounts and improved availability of nutrients.
- Act as a carbon sink by binding organic carbon, aiding efforts to mitigate climate change.
- Enhance its structure through the aggregation of soil particles, which helps prevent erosion.
- Improve aeration, which also boosts its ability to absorb and retain water—an increasingly important function due to more frequent extreme weather events like droughts and heavy rains.
- Combat low micronutrient levels in food by ensuring the presence of essential vitamins and trace minerals.

The preservation of soil microorganisms is essential for maintaining fertile soils and ensuring reliable crop yields. Healthy soils are foundational not only for agricultural productivity but also for the functioning of natural and semi-natural ecosystems. However, the critical topic of belowground soil biodiversity often remains underappreciated in public debates on climate and sustainability, which tend to focus more on carbon emissions and aboveground biodiversity.

Research in soil biodiversity is still in its infancy. Both academic institutions and the R&D divisions of large agricultural companies have traditionally concentrated on plant physiology and the impacts of aboveground factors on crop health and yield. As a result, there is limited understanding of the complex interactions below the surface. Only about 1% of soil (micro)organisms have been identified, even though soil is home to more than half of all living microorganisms on Earth.

To move forward, it is imperative to establish clear knowledge of and targets for biodiversity within agricultural ecosystems. This will not only enhance sustainable agriculture practices but also contribute significantly to global food security and environmental health.



Introduction

Have you ever thought about the value of soil? It covers 25% of the earth's surface. It supports all our ecosystems, from farms and grazing land to rainforests and the vast northern taiga. It contains more carbon than the earth's atmosphere and all its plant biomass combined. The amount of fresh water in soil that's available to plants is 100 times greater than all the world's lakes, rivers, and wetlands combined. Soil connects the lithosphere, atmosphere, hydrosphere, and biosphere. And 95% of the food we eat is dependent on it, making it the single most important resource for agriculture to feed the world.

Yet despite its importance, we are only just beginning to understand the science of soil: its astonishing biodiversity when healthy and the role it plays not just in the production of food but in maintaining clean fresh water, recharging groundwater reserves, and collecting and storing the carbon that would otherwise keep warming the planet.

What we have learned, however—not just about the conditions needed for the healthiest, most productive soil possible but also about the significant economic value to be gained by improving it (upward of €14 billion a year in Germany alone)—makes clear just how critical it is to strive in every way to optimize and maintain its health.

This is a task for all stakeholders—not just farmers, agronomists, and agricultural policymakers but also for agricultural input and food companies, grocers, and consumers. More research is required to determine the conditions needed to promote soil biodiversity and set standards for maintaining soil health. Companies and investors across the agricultural value chain need to boost efforts to improve soil conditions. And governments should define policies and incentives to support biodiversity practices.

In this report we look at what makes healthy soil so critical to the well-being of the planet and how all stakeholders can work together to capture its considerable economic value.



Why Soil Matters

Soil and the organisms that live within it form the bedrock of life on Earth. Healthy soil is fundamental to sustainable agriculture, providing a myriad of ecosystem benefits that extend far beyond the nourishment and protection of crops. It filters our drinking water, mitigates the impact of heavy rains, enhances the nutrient cycle, and is essential for growing healthy food.

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Covering around 25% of the Earth's surface, soil is a crucial natural resource. It supports 59% of all terrestrial life, from surface-dwelling insects to microscopic organisms living underground. And all this abundance thrives within the top 15–25 centimeters of the Earth's crust.

Consider these facts:

- Soil contains more carbon than the atmosphere and all plant biomass combined.[1]
- The amount of fresh water in soil available to plants (excluding ice, snow, and permafrost) is 100 times greater than all the planet's lakes, rivers, and wetlands combined.[2]
- Fully 95% of our food is dependent on soil, making it the single most important resource for feeding the world's population.[3]
- New York City benefits from as much as $8.5 billion in savings on water filtration infrastructure by leveraging the natural filtration performed by healthy soil.[4]

Soils rank among the most biologically diverse habitats on Earth. While we often focus on aboveground biodiversity, belowground biodiversity is staggering by comparison: one teaspoon of soil contains more microorganisms than there are humans on Earth.[5]

These insights underscore the tremendous value of soil and its biodiversity. Healthy soils are indispensable to sustainable agriculture, delivering essential ecosystem services that support terrestrial life and ensure the resilience and productivity of our agricultural systems.

1. European Commission, *Soil: The Hidden Part of the Climate Cycle*, 2011.
2. GERICS, "Wasservorräte," 2008, **https://wiki.bildungsserver.de/klimawandel/index.php/Datei:Wasservorraete.jpg**.
3. S. Confer, "Fascinating Soil Facts: 23 Amazing Facts About Soil," Nomomente, 2021.
4. US Environmental Protection Agency, "The Economic Benefits of Protecting Healthy Watersheds," EPA 841-N-12-004, 2012.
5. C. Sprunger, "Deteriorating Soil Health: 'A Teaspoon of Soil Contains More Life Than There Are Humans on Earth," *Open Access Government*, 2022.

The Magic of SOM

Soil is a complex and heterogeneous system, an aggregate of mineral and organic components that create a rich habitat for soil organisms. This diverse habitat, comprising pores of different sizes filled with air and water, supports an incredible range of organisms of varying sizes and ecological niches. Germany alone, for example, is made up of 12 distinct landscape regions, including coastal land, floodplains, moraines, and mountains—each encompassing multiple soil types. (**See the sidebar "Germany's Soil Richness."**)

Across all types, soil is typically composed of about 45% minerals, 25% air, and 25% water. The remaining 3% to 7% is called soil organic matter (SOM), which serves as the engine for creating healthy and fertile soil (**see Exhibit 1**). The actual amount of SOM varies depending on the soil's texture and composition as well as external factors such as temperature.

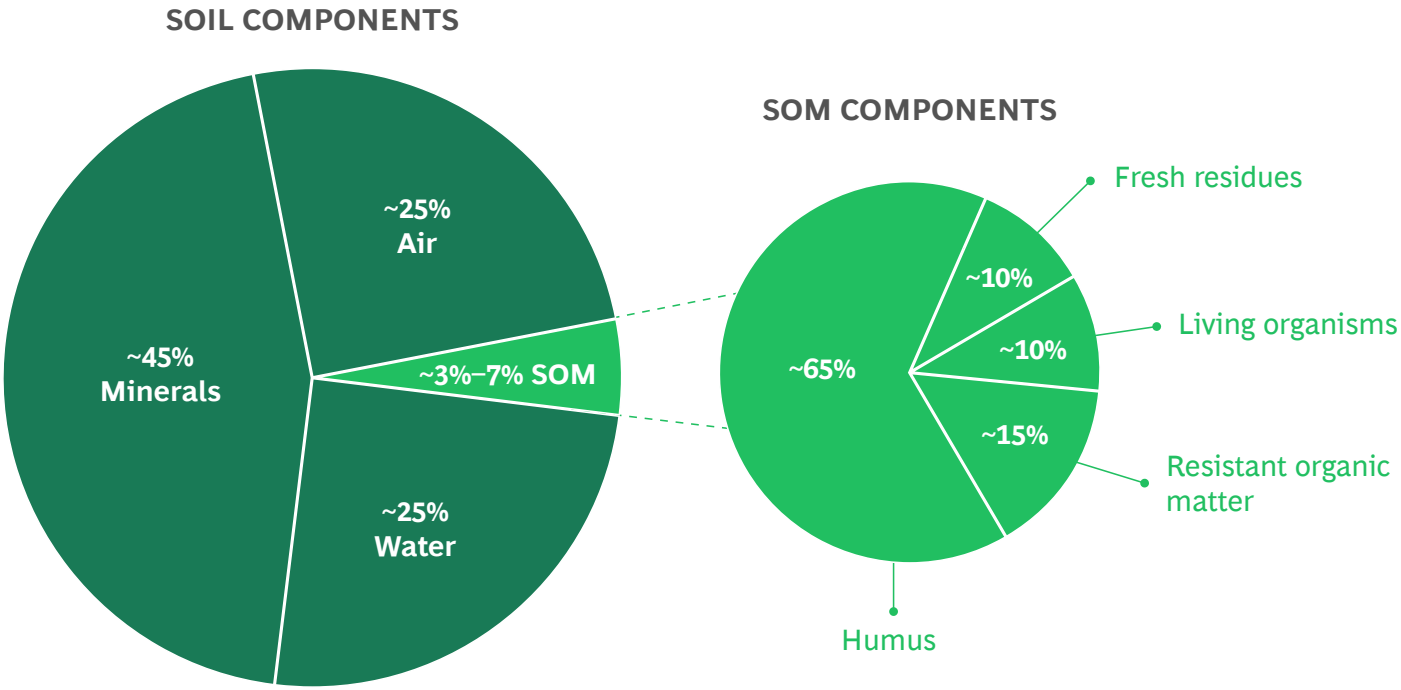
SOM comprises four distinct components: living organisms, biomass (which is made up of fresh plant residues), resistant organic matter, and humus (which is created through the decomposition of biomass).

SOM's various functions are primarily supported by the humus, a stable form of organic matter that makes up about 65% of SOM. Humus is a vital component of fertile soil, as it contains and cycles nutrients, stores water, sequesters carbon, and stabilizes soil structure. Living microorganisms make up only about 10% of SOM but are the key catalysts for turning fresh biomass into SOM and keeping the cycle going.

An adequate proportion of high-quality SOM, with a high ratio of humus, is the key to healthier soil and higher crop yields. SOM contributes to robust soil structure; protects against erosion, stores and regulates water, air, and nutrients; and sequesters carbon. It supplies resources for microbes and other soil organisms, increases the nutrients available to plants, and maintains the pH balance of the soil, reducing the high acidity levels that make it difficult—and sometimes even impossible—for plants and microorganisms to survive.

EXHIBIT 1

Soil Organic Matter (SOM) Makes Up Just 3% to 7% of Soil, but It's Key to Soil's Health



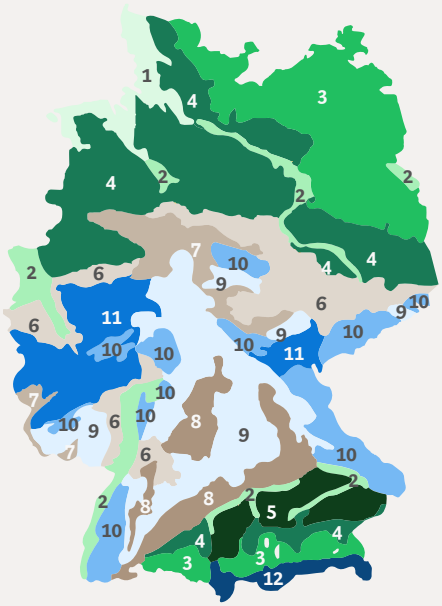
Sources: NABU; BCG analysis.

Germany's Soil Richness

Germany's 12 distinct landscape regions reflect the country's varied topography, climate, and geological history. There are 18 different soil types across these areas, each distinguished by its properties and where it occurs (**see the exhibit "Germany Is Made Up of 12 Distinct Landscape Regions and Multiple Soil Types"**). Key differentiators among these soil types include properties such as nutrient content and chemical composition, texture and bulk density, rates of SOM buildup, and the levels at which their SOM reaches equilibrium.

Consequently, different soil types can best support different agricultural practices and cropping systems. The water-holding capacity of podzol and sandy soils, for example, is low, making them favorable for crops such as roots and tubers, which dislike overly wet conditions or require certain dry conditions for harvesting. Heavier soils, on the other hand, typically have a higher clay content, resulting in a higher capacity to hold water and retain nutrients. These soil types are best suited for perennial crops and for nutrient-demanding cereals and vegetables.

Germany Is Made Up of 12 Distinct Landscape Regions with Multiple Soil Types



Landscape regions	Most common soil types
1 Coastal Holocene	Tidal flats, marshes, podsol-regosol, lose syrosem
2 Interregional floodplain landscapes	Alluvial soil, gley, parabrown earth, brown earth, pararendzina
3 Young moraine landscapes	Parabrown earth, fahlerde, pseudogley, brown earth, gley, podsol
4 Old moraine landscapes	Brown earth, podsol, pseudogley, parabrown earth, gley, moor
5 Gravel cover plates and tertiary hill country in the alpine foothills	Brown earth, parabrown earth, pseudogley, grey, pararendzina
6 Loess and sand loess landscapes	Parabrown earth, chernozem, pseudogley, fahlerde, pararendzina
7 Mountain and hill country with a high proportion of unmetamorphosed sedimentary rocks	Parabrown earth, rendzina, brown earth, ranker, pseudogley
8 Mountain and hill country with a high proportion of unmetamorphosed carbonate rocks	Rendzina, pararendzina, brown earth, parabrown earth, pseudogley
9 Mountain and hill country with a high proportion of unmetamorphosed sand, silt, clay, and marl rocks	Brown earth, podsol, parabrown earth, pseudogley, pelosol
10 Mountain and hill country with a high proportion of magmatites and metamorphites	Brown earth, podsol, pseudogley
11 Mountain and hill country with a high proportion of clay and schist shales	Brown earth, pseudogley
12 Alps	Rendzina, pararendzina, syrosem, brown earth, pseudogley, ranker

Sources: NABU; BCG analysis.

Our study focuses on the four most common soil clusters in Germany—brown earth, parabrown soil, podzol, and gley—each of which contributes uniquely to the country's agricultural ecosystem (**see the exhibit "Germany Contains Four Main Soil Types, Based on Shared Properties and Features"**).

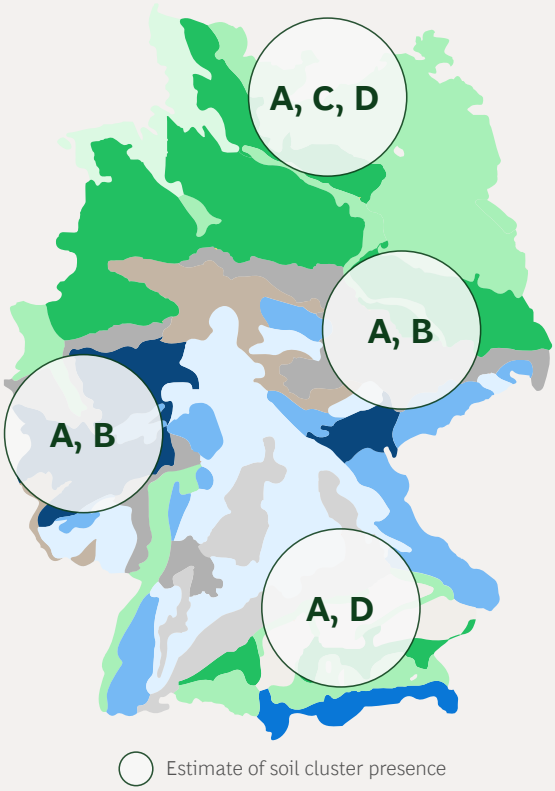
- **Brown earth.** Predominantly found in low mountain ranges and hilly landscapes across Germany. These soils are well aerated and have a moderate-to-good nutrient supply, with pH levels ranging from neutral to slightly acidic. They typically contain between 2% and 5% SOM, which can increase by 0.1–0.2 percentage points annually if it is below the equilibrium state.
- **Parabrown soil.** Primarily occurs in the western and eastern regions of Germany. These soils are rich in nutrients, have high water-holding capacity, and are deep and easy to root. The SOM content in parabrown soil typically ranges from 2% to 6%, increasing annually by 0.2–0.4 percentage points.
- **Podzol.** Predominantly found in northern Germany, these soils are highly acidic, low in nutrients, and often humus-poor, with a washed-out layer underneath. The SOM content in podzol ranges from 1% to 3%, with an annual SOM increase of 0.05–0.1 percentage points.
- **Gley.** Mainly found in lowlands, floodplains, and areas with a higher water table, mostly in southern Germany. These soils are periodically wet, high in humus content, and poorly aerated. The SOM content in gley soils ranges from 3% to 7%, increasing 0.1–0.2 percentage points annually.

Germany Contains Four Main Soil Types, Based on Shared Properties and Features

Soil clusters

- A Brown earth
- B Parabrown soil
- C Podzol
- D Gley

Predominant presence of soil clusters



Sources: NABU; BCG analysis.

The Three Natural Cycles

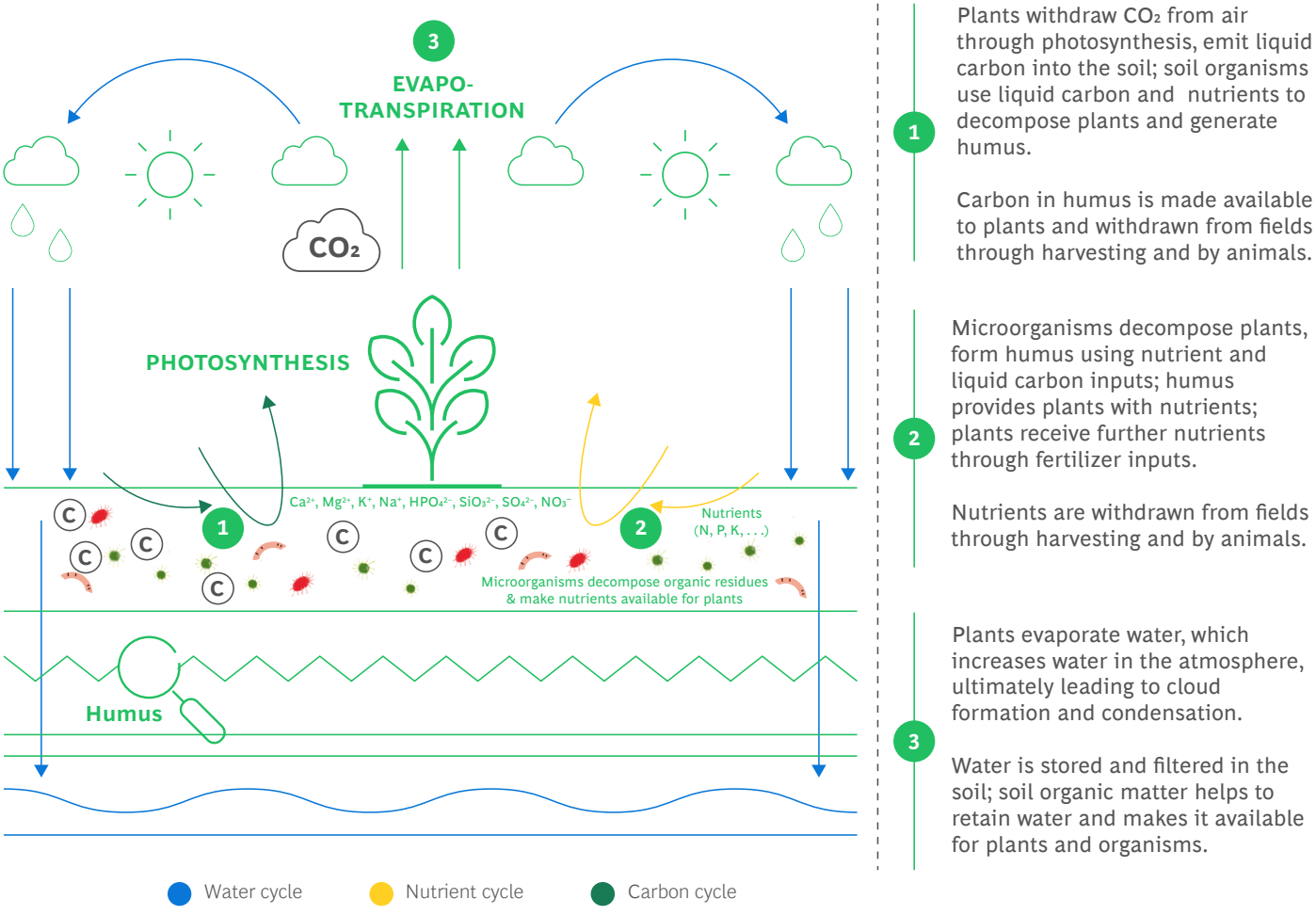
The creation and maintenance of healthy SOM both depends on and helps support the three critical natural and closely interconnected cycles: water, carbon, and nutrient (**see Exhibit 2**).

Water Cycle. There are two water cycles: the small water cycle and the more familiar large water cycle. Each plays a crucial role in maintaining the Earth's climate and supporting ecosystems.

The large water cycle operates on a global scale, moving water between the oceans, the atmosphere, and land. It begins when water evaporates from oceans, rivers, and lakes into the atmosphere. This vapor cools and condenses into clouds, leading to precipitation—rain or snow—that replenishes water on land. On land, precipitation either seeps into the soil or flows as runoff into rivers, eventually returning to the oceans. This global system regulates weather patterns and helps distribute water across vast distances.

EXHIBIT 2

SOM Both Depends On and Helps Sustain the Water, Carbon, and Nutrient Cycles



Sources: NABU; BCG analysis.
Note: Diagram is not to scale. C = carbon; Ca^{2+} = calcium; CO_2 = carbon dioxide; HPO_4^{2-} = hydrogen phosphate; K^+ = potassium; Mg^{2+} = magnesium; N = nitrogen; Na^+ = sodium; NO_3^- = nitrate; P = phosphorus; SiO_3^{2-} = silicate; SO_4^{2-} = sulfate.

The small water cycle involves the movement of water between the soil, plants, and atmosphere and operates within localized ecosystems. Plants play a central role through transpiration—the process of releasing water vapor from their leaves during photosynthesis. This vapor contributes to local humidity, which eventually condenses into clouds and precipitates as local rainfall. The small water cycle is also critical for the local microclimate, as water evaporation has a crucial cooling effect at the hyper-local level.

Healthy soils and abundant vegetation are essential for the small water cycle to function. Soils rich in organic matter act like a sponge, absorbing rainwater and slowly releasing it back into the atmosphere through transpiration. This cycle supports consistent rainfall, regulates local temperatures, and sustains plant growth. When soils are left bare, however, the small water cycle breaks down. There's little transpiration, leading to less local rainfall. Barren soils also heat up faster, which accelerates the drying of the landscape.

Increasing soil organic carbon (SOC—the amount of carbon in the soil's SOM) creates a soil carbon sponge that can hold more water, resulting in higher soil moisture levels and hence greater resilience against severe weather patterns. Increased soil moisture levels help crops to better withstand heat stress and temporary droughts. This helps soils to better absorb rainfall, reduce runoff, and sustain plant growth, which in turn boosts transpiration and revives the small water cycle.

Carbon Cycle. Plants absorb CO_2 from the atmosphere and, through photosynthesis, convert it into sugars, which contain carbon. This carbon is then made available to organisms in the soil in two primary ways: through the release of liquid carbon through the roots and through the decay of plant biomass (the "liquid carbon pathway" concept). Soil organisms use this biomass and nutrients from plants to decompose organic material, converting it into humus and fixing carbon in the soil as SOC, a crucial component of humus. Under the right conditions, 30% to 40% of the carbon fixed via green leaves can be transferred to soil and rapidly stabilized when turned into humus, resulting in the sequestration of carbon of up to 5 and even 20 tons of CO_2 per hectare per year.[6] **(See the sidebar "The Miracle of Carbon.")**

In healthy soils, the SOM content is typically within a stable range of 4% to 7%, depending on climatic conditions and soil type. This range is influenced by the balance between the accumulation of organic matter through plant biomass and its decomposition and conversion into CO_2 by microbial activity, which is then released into the atmosphere. In colder climates, SOM levels tend to be higher because microbial respiration is minimal during sub-zero winter temperatures. In tropical regions, however, the constant high microbial activity throughout the year leads to faster decomposition rates and consequently lower SOM levels.

While increasing SOM is possible and beneficial for soil health and carbon storage, it is important to note that carbon levels in soil cannot be increased infinitely, as carbon is also released back into the atmosphere through microbial respiration and taken out of the cycle through the harvesting of crops. Even in untouched ecosystems, the amount of organic matter eventually reaches a steady state where inputs from plant biomass are balanced by losses due to microbial respiration and other natural processes.

Below these natural levels, as is sometimes the case of agricultural soils with low levels of carbon, microbial processes and amendments of biomass can increase SOM, provided that the conditions favor the accumulation of organic matter and are not hindered by human activities such as tillage or the excessive removal of biomass through intensive practices like double-cropping. To ensure a net gain in SOM, management practices must optimize factors such as plant biomass input and minimize disruptions to soil structure and microbial communities.

This dynamic balance underscores the need for careful soil management to maximize carbon sequestration while recognizing the natural boundaries imposed by ecological processes.

Nutrient Cycle. A number of nutrients exist in different forms above ground. For instance, nitrogen is present in the atmosphere as nitrogen gas (N_2), while phosphorus is found in sediments such as rocks. In this cycle, these nutrients are captured and absorbed into the soil through microbial activity. Bacteria like *Rhizobium* and cyanobacteria play a pivotal role in fixing atmospheric nitrogen in the soil, while phosphorus enters the soil through the weathering of rocks. Combined with the carbon emitted from plant roots, these nutrients form the essential building blocks that soil organisms need in order to produce humus. The nutrients in humus are subsequently absorbed by plants and released from the cycle as crops are harvested or fed back into the soil through plant residues left in the fields.

6. C. Jones, "Liquid Carbon Pathway," **https://www.amazingcarbon.com/PDF/JONES-LiquidCarbonPathway(July08).pdf**.

The Miracle of Carbon

Healthy soils depend on the continuous formation of humus, the soil component that stores carbon and nutrients. According to the liquid carbon pathway concept,[1] plants, soil, and microorganisms work together in a dynamic process to break down plant matter into biomass and ultimately create humus, maintaining the necessary balance that supports soil health and plant growth.

This path begins with photosynthesis, where plants capture CO_2 from the air and convert it into sugars. Some of these sugars are stored in the plants' stems and leaves, forming biomass, while others are sent to the roots and exuded into the soil. These root exudates feed microorganisms in the soil, which, through their metabolic activities, release the nutrients plants need and help stabilize carbon in the form of humus.

The formation of humus involves more than carbon; minerals in the soil also play an essential role in stabilizing humus and enhancing its nutrient-holding capacity. Plant biomass, such as dead leaves, stems, and roots, is broken down into smaller components by soil organisms. Microorganisms and fungi then process these simpler compounds and bind them with minerals such as calcium, magnesium, and iron. These minerals help form stable organo-mineral complexes that give humus its long-lasting properties. This combination allows soils to retain nutrients and water more effectively, which is critical for plant growth and ecosystem resilience.

Fungi are particularly important in this process, as they facilitate the exchange of nutrients between plants and soil while helping to stabilize carbon in organo-mineral complexes. The mineral components give the humus structure and longevity, ensuring that carbon and nutrients remain in the soil for extended periods, sometimes hundreds of years.

If plants stop releasing sugars into the soil—for example, during periods of poor plant growth—microorganisms will decompose existing humus to release nutrients, which plants can then use to grow. Over time, this process allows carbon and nutrients to reach deeper layers of soil, contributing to soil health in the long term.

To encourage this natural soil-building process, farmers can adopt practices that support soil life, such as minimizing soil disturbance, planting a variety of cover crops, and rotating different crops. These methods help keep the soil biologically active and maintain its ability to store carbon and nutrients, essential ingredients for sustainable farming.



1. C. Jones, "Liquid Carbon Pathway," **https://www.amazingcarbon.com/PDF/JONES-LiquidCarbonPathway(July08).pdf**.



Why Biodiversity Matters

All the elements of soil described above—the humus and other ingredients of SOM, the three cycles and the conditions that promote them—must come together in the proper proportion to create adequate biodiversity, the most important factor for healthy soil. We define soil biodiversity as the variety of living organisms in the soil, including their genetic differences, species, communities, and the diverse habitats they occupy.

Biodiversity is multidimensional, involving the variety and variability of life at genetic, species, and ecosystem levels.[7] Soil biodiversity, as defined by the Convention on Biological Diversity, encompasses the diversity of life within soil, ranging from genes to entire ecosystems, including the complex interactions within soil habitats. On the genetic level, it denotes the number, or richness, of distinct species and their relative evenness of distribution.

The degree of biodiversity in soil depends on the variety of organisms it contains. Each type of soil fauna plays a distinct but interconnected role in maintaining soil health and fertility.

- **Microfauna ("Decomposers").** This group includes a wide range of microscopic chemical engineers, including viruses, bacteria, archaea, and fungi, that are found within the soil and the water that percolates through it. These microorganisms are vital for decomposing SOM and weathering minerals in the soil, making them accessible to plants. Their diversity is influenced by the conditions of their microhabitat and the physicochemical properties of the soil layers.
- **Mesofauna ("Shredders" and "Fungal and Bacterial Feeders").** Mesofauna—including mites, springtails, enchytraeids (small worms), apterygota (wingless insects), and small insect larvae—are soil's biological regulators. Their primary role is to contribute to the breakdown of SOM, fragmenting larger pieces of organic material, which increases the surface area for microbial decomposition. This process helps release nutrients back into the soil, making them available for plant uptake. The movement of mesofauna through the soil helps mix organic and mineral components, improving soil structure and aeration. In addition, mesofauna such as protozoa and larger nematodes play key roles in feeding on bacteria and fungi, contributing significantly to the microbial loop, decomposing SOM, and recycling and releasing nutrients in forms that plants can absorb.
- **Macrofauna ("Predators").** These organisms function as the soil's ecosystem engineers. Macrofauna include organisms such as earthworms, beetles, termites, and ants. They aid in the decomposition process by breaking large pieces of SOM into smaller particles. Their burrowing activities create channels in the soil, improving aeration, water infiltration, and root penetration. Macrofauna also help distribute and mix decomposed SOM throughout the soil, incorporating nutrients and enhancing soil fertility. Earthworms, for example, significantly alter the physical and chemical properties of the soil through their movements and digestion, benefiting plant growth and other soil organisms.

7. T. Kurth et al., *The Biodiversity Imperative for Business: Preserving the Foundations of Our Well-Being*, BCG, 2020.



The Recipe for Healthy SOM

Maintaining adequate, stable soil biodiversity is critical if farmers, food companies, and consumers are to reap the benefits of healthy soil. This requires ensuring that the soil's SOM, too, is as healthy as possible. Healthy SOM is affected to varying degrees by six major belowground factors: sufficient moisture, right texture and structure, sufficient organisms, sufficient biomass, right pH, and temperature (**see Exhibit 3**). And each of these factors can be influenced to varying degrees by a range of aboveground factors, including environmental conditions and farming practices (**see Exhibit 4**). (**See the sidebar "The Role of Aboveground Agricultural Practices."**)

Sufficient Moisture

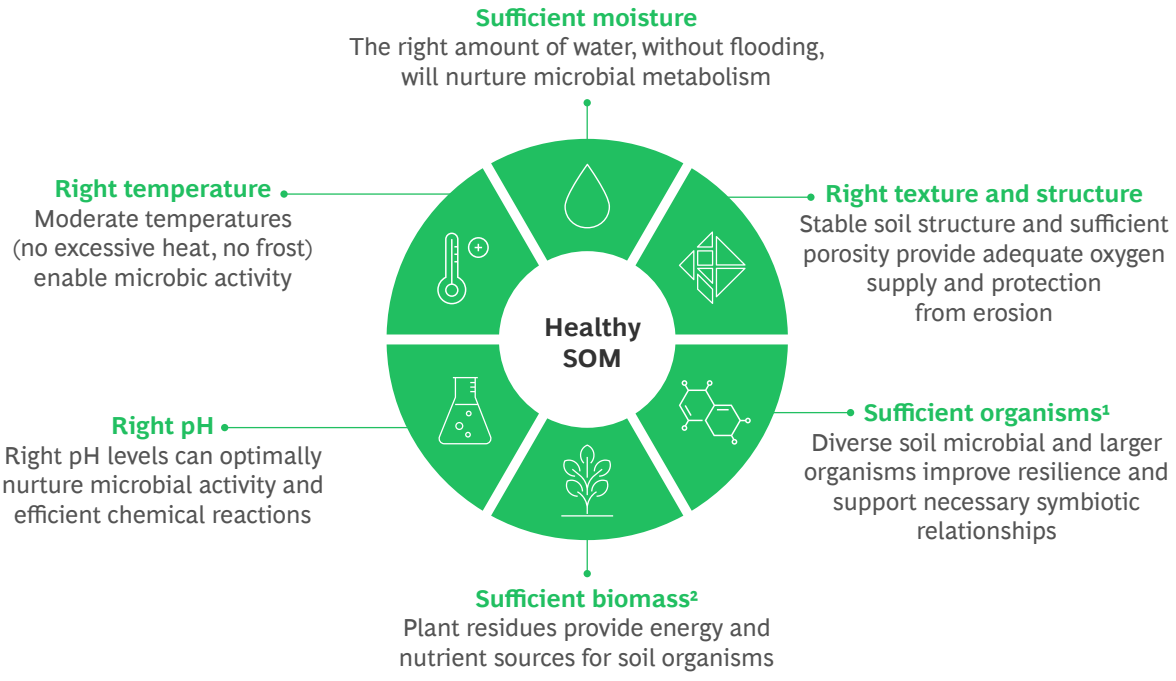
- **High Belowground Impact.** Adequate moisture in the soil is key to the survival of the soil's organisms and their metabolism. Water is also the main means of transport for nutrients; between microorganisms and plants, for example.
- **High Aboveground Influence.** Various farming practices significantly affect the availability of humidity below ground. Cover crops and agroforestry help keep the soil moist, especially during dry conditions, when they also reduce the risk of runoff. Minimizing tillage helps maintain soil structure, thus increasing water uptake. And constructing water dams between crop fields can increase water availability during droughts.

Right Texture and Structure

- **High Belowground Impact.** Soil texture and structure are critical belowground factors for high-quality SOM. Ideal soil textures have high silt or clay content and sufficient humus. Clay particles have a large surface area, increasing water and nutrient retention. The oxides found in clay bind nutrients and stabilize soil particles. High mineral content enhances nutrient retention and water holding capacity. And humus is resistant to decomposition, stores water, nutrients, and carbon, binding soil particles together. Good soil structure is characterized by low compaction, which enhances water infiltration, nutrient retention, and root development.
- **Moderate Aboveground Influence.** Supportive farming practices include minimizing tillage, which helps maintain soil structure, while crop rotation and agroforestry can enhance soil structure and reduce erosion risks. Applying soil boosters such as biologically activated biochar (carbonized biomass inoculated with microbes) improves nutrient availability and increases carbon capture.

EXHIBIT 3

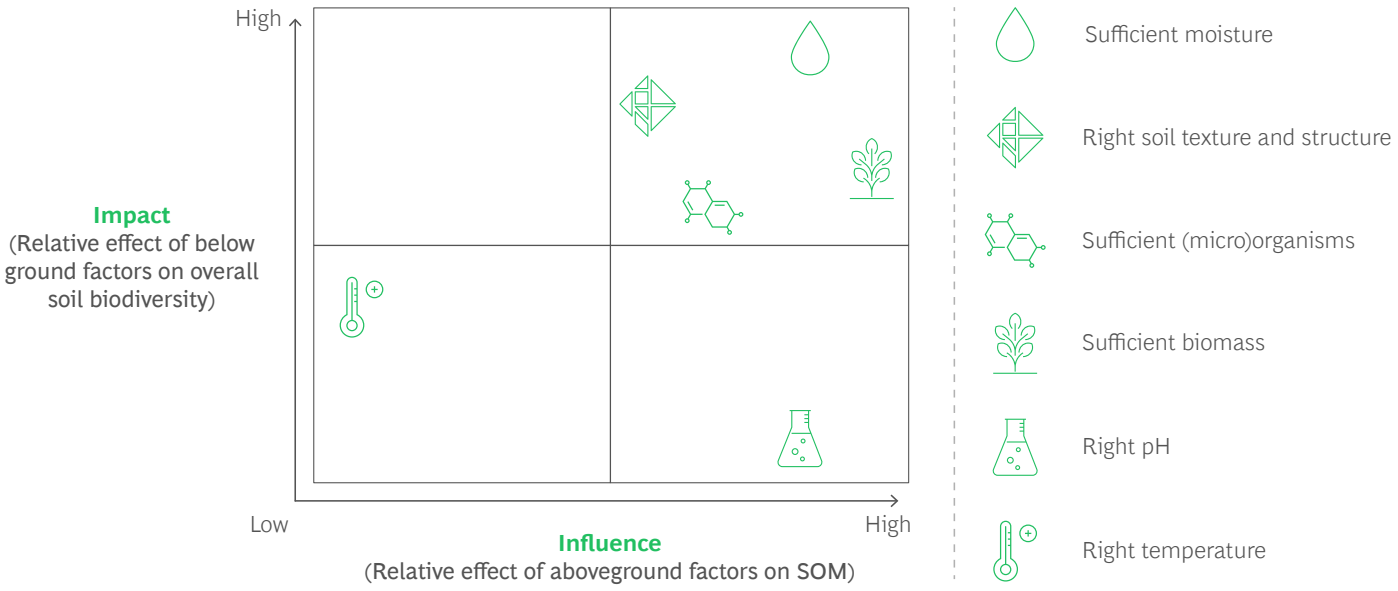
The Recipe for Healthy Soil Organic Matter Is Based on Six Key Ingredients



Sources: NABU; BCG analysis.
[1]In the context of soil biodiversity, microorganisms include earthworms, fungi, nematodes, bacteria, etc.
[2]Here, biomass refers to dead biomass only.

EXHIBIT 4

The Majority of SOM Factors Have a High Impact on SOM Biodiversity and Can Be Influenced Significantly by Aboveground Factors



Sources: NABU; BCG analysis.

The Role of Aboveground Agricultural Practices

The fertility and biodiversity of agricultural soil is closely interconnected to its aboveground environment. And as our 2023 study, "The Case for Regenerative Agriculture in Germany—and Beyond," made clear, there are a number of aboveground agricultural practices that are strongly correlated with healthy soil **(see the exhibit)**.

These include:

- **Minimal Tillage.** The physical disturbance caused by tilling the soil before planting breaks up the soil's structure and destroys aggregates and soil pores, leading to increased soil compaction and reduced SOM buildup. Tilling also disrupts the existing channels created by dead roots, earthworms, and other animals, negatively impacting water infiltration, storage, and habitat. Overall, undisturbed soil structure increases soil health and biodiversity.

- **Cover Cropping.** Planting cover crops after harvesting ensures that the soil is permanently covered with either mulch or living plants. This protects the soil from erosion by wind and water, reduces evapotranspiration and cooling, builds up organic matter, promotes soil biodiversity, and reduces the need for fertilizers.

- **Crop Rotation.** Much like cover cropping, crop rotation provides soil coverage and thus reduces the risk of erosion, cools the soil, and helps to build up SOM. Crop rotation also recalibrates the soil, relieving pressure on specific nutrients and increasing fertility. And it supports the growth of a wide array of organisms, thereby contributing to greater soil biodiversity.

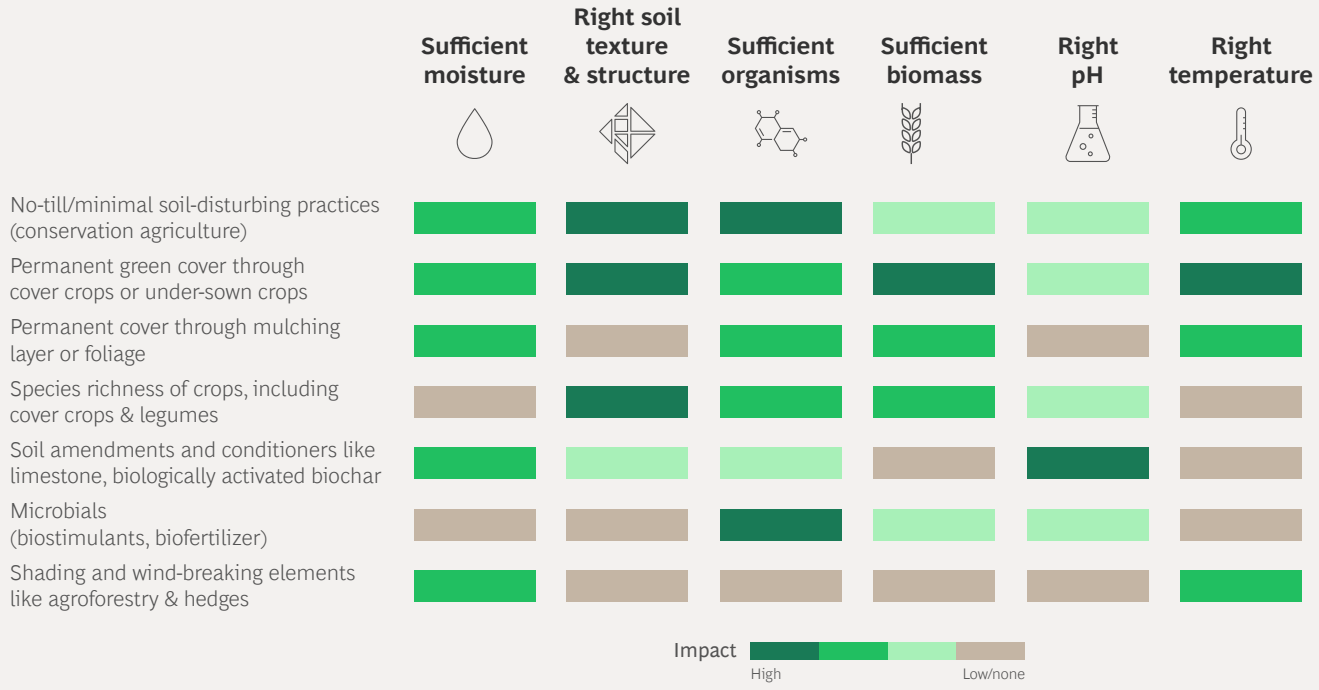
- **Agroforestry.** The incorporation of agroforests and hedges improves soil structure and water retention and helps manage the total amount of available water in the soil by absorbing excess rainwater. Agroforests also provide shade for plants and protect the soil against erosion caused by extreme weather, such as wind. Hedges help to build up a microclimate, provide refuge for animals, and reduce wind and evapotranspiration.

- **Water Dams.** Water dams between fields improve available water during droughts, thereby reducing the risk of soil erosion and the destruction of soil structure.

- **Soil Boosters.** Boosting soil health through various amendments can be crucial. This includes biologically activated biochar—carbonized biomass inoculated with microbes that when added to the soil can improve soil structure and nutrient-holding capacity. Black mulch films, using shredded cover crops as mulch covered by black plastic films, help retain nutrients, absorb heat, and increase soil temperature. In addition, introducing beneficial organisms such as mycorrhizal fungi inoculants and earthworms improves biodiversity and overall soil health.

Better Farming Practices Lead to Healthier Soil in Six Key Areas

Soil Biodiversity



Sources: NABU; BCG analysis.
Note: Biologically activated biochar = carbonized biomass inoculated with microbes.

Sufficient Organisms

- **High Belowground Impact.** The organisms in SOM are responsible for biomass decomposition, carbon sequestration, and nutrient cycling. Healthy SOM contains the right balance of beneficial, neutral, and harmful organisms.

- **High Aboveground Influence.** Helpful agriculture practices include planting cover crops; these release nutrient and carbon inputs into the soil and enhance microbial activity, thereby boosting carbon sequestration. Soil boosters, including earthworms, mycorrhizal fungi inoculants, and specific biostimulants, improve organism diversity, contributing to a healthy level of biodiversity.

Sufficient Biomass

- **High Belowground Impact.** Sufficient biomass is essential for maintaining healthy SOM, as it is the fuel for the soil's organisms' activities. Below ground, biomass ensures sufficient levels of SOC and provides a healthy environment for organisms. Biomass contains cellulose, such as carboxycellulose, which is able to bind ions, enabling it to filter water by binding toxic ions and increase nutrient capture. Biomass also plays a crucial role above ground by protecting the soil surface from wind, soil cracking, evaporation, and water erosion.

- **High Aboveground Influence.** Several farming practices can support the soil's biomass. Minimizing tillage helps maintain soil structure and the destruction of organisms, thereby supporting the decomposition of biomass. Cover crops increase the available biomass. And soil boosters, including the planting of fast-growing biomass crops such as willows can increase the rate of biomass production.

Right pH

- **Low Belowground Impact.** A healthy SOM depends on a balance of the crops' optimal pH level for macronutrients such as nitrogen and potassium, micronutrients such as copper and zinc, and the ability of crops to absorb both nutrients and water. The right pH level affects various soil functions such as crop growth, nutrient availability and mobility, and microbial activity. Thus, pH levels have a direct effect on carbon sequestration, which is primarily driven by soil decomposition by organisms.

- **High Aboveground Influence.** Farming practices that affect soil's pH level include adding basic soil boosters such as chalk or limestone—which contain calcium, magnesium, and other minerals that increase the pH—or acidic sulfur, which lowers it. In addition, increasing the available biomass can increase pH buffer capacity, enabling the soil to mitigate external pH shocks such as higher acidity levels in rain.

Right Temperature

- **Moderate Belowground Impact.** High soil temperatures boost microbial activity, accelerating the decomposition of SOM. Conversely, low soil temperatures decrease microbial activity, reducing the availability of essential minerals and nutrients needed for plant growth. Extremely low temperatures, such as frost, kill organisms and reduce water absorption rates, hindering water uptake and retention.

- **Low Aboveground Influence.** Most aboveground farming practices have little effect on soil temperatures, but some can influence temperature to a certain degree. Incorporating agroforests or hedges into cropland can provide a cooling effect, as can planting cover crops, which can reduce surface temperatures by up to 20 degrees.[8] Adding black mulch to the soil surface can increase soil temperatures.

8. P. Hesslerová et al., "Daily Dynamics of Radiation Surface Temperature of Different Land Cover Types in a Temperate Cultural Landscape: Consequences for the Local Climate," *Ecological Engineering*, May 2013.

When one or more critical factors for healthy SOM are out of balance, it becomes impossible to maintain healthy and fertile soil suitable for agriculture. Deserts, for example, don't get enough rain, and the structure of desert soil is loose and unstable, hindering retention of the water they do receive. As a result, they can't sustain the vegetation required to produce adequate biomass and to maintain the carbon cycle that would enable them to build a healthy layer of SOM. In contrast, the excess water in peatlands negatively affects the soil's biodiversity and pH levels, hindering the development of healthy soil layers for the productive cultivation of crops but boosting peatlands' important role as a carbon sink **(see Exhibit 5)**.

More than half of global soil is not in a healthy state, and 40% is classified as degraded.[9] Degraded soils are deficient in a variety of nutrients, contain little SOM and have much less biodiversity than healthy soils. As a result, they are more prone to adverse environmental effects. Because they are typically far less capable of absorbing water than healthy soils, they are subject to both wind erosion and heavy rain events, leading to flooding and topsoil erosion.

More than half of global soil is not in a healthy state, and 40% is classified as degraded, thus more prone to adverse environmental effects.

Under the most extreme conditions, the negative effects of degraded soils lead to desertification, where almost no plants can grow. While this outcome is considered primarily an issue in specific subtropical zones, including parts of China and the Sahel, it is becoming more widespread even in temperate regions such as Europe and North America. For example, deforestation, poor soil management, and the impact of climate change have badly degraded the soil in Romania's Dobrogea region. Heat stress and the increasing frequency of droughts have hit the area severely, reducing vegetation cover and soil moisture levels. As a result, wind and water erosion is causing dramatic soil losses, as the dry and crusted surface is unable to absorb water when it does rain. Altogether, about 3 million hectares of Romania's surface area—and 2.8 million hectares of its cropland—are at acute risk of desertification.[10]

EXHIBIT 5

Imbalance of SOM Factors Leads to Extreme Soil Types

Desert	Peatland	Permafrost	Wetland
! **Texture & structure** Loose and unstable structure	! **Texture & structure** Loose and unstable structure	! **Soil structure** Frozen surface with less infiltration of water	! **Soil structure** Loose and unstable structure
! **Water** Dry conditions with reduced AWHC	! **Water** Too much water, leading to nutrient leaching	! **Microorganisms** Missing soil biome with anaerobic environment	! **Water** Too much water, leading to nutrient leaching
! **Biomass** Missing biomass as food for soil biome	! **pH** Too-acidic soil environment	! **Temperature** Cold, causing reduced microbial activity	! **pH** Too-acidic soil environment

Sources: NABU; BCG analysis.
Note: AWHC = available water holding capacity.

9. United Nations Convention to Combat Desertification, "Chronic Land Degradation," press release, April 26, 2022.
10. Romania Ministry of Agriculture, Food, and Forests, "National Report on the Implementation of the United Nations Convention to Combat Desertification (UNCCD) in Romania," Bucharest, 2002.

Maintaining adequate, stable soil biodiversity is critical if farmers, food companies, and consumers are to reap the benefits of healthy soil.



Measuring Soil Biodiversity

Soil is the most biodiverse habitat on earth, which is one reason that quantifying its biodiversity remains a challenge. It is estimated that between 25% and 60% of life on Earth resides in soil.[11] Besides the high variation of life forms, quantifying soil biodiversity is hampered by the low level of research focus on belowground biodiversity as compared to aboveground flora and fauna and the absence of standardized measurement methods.

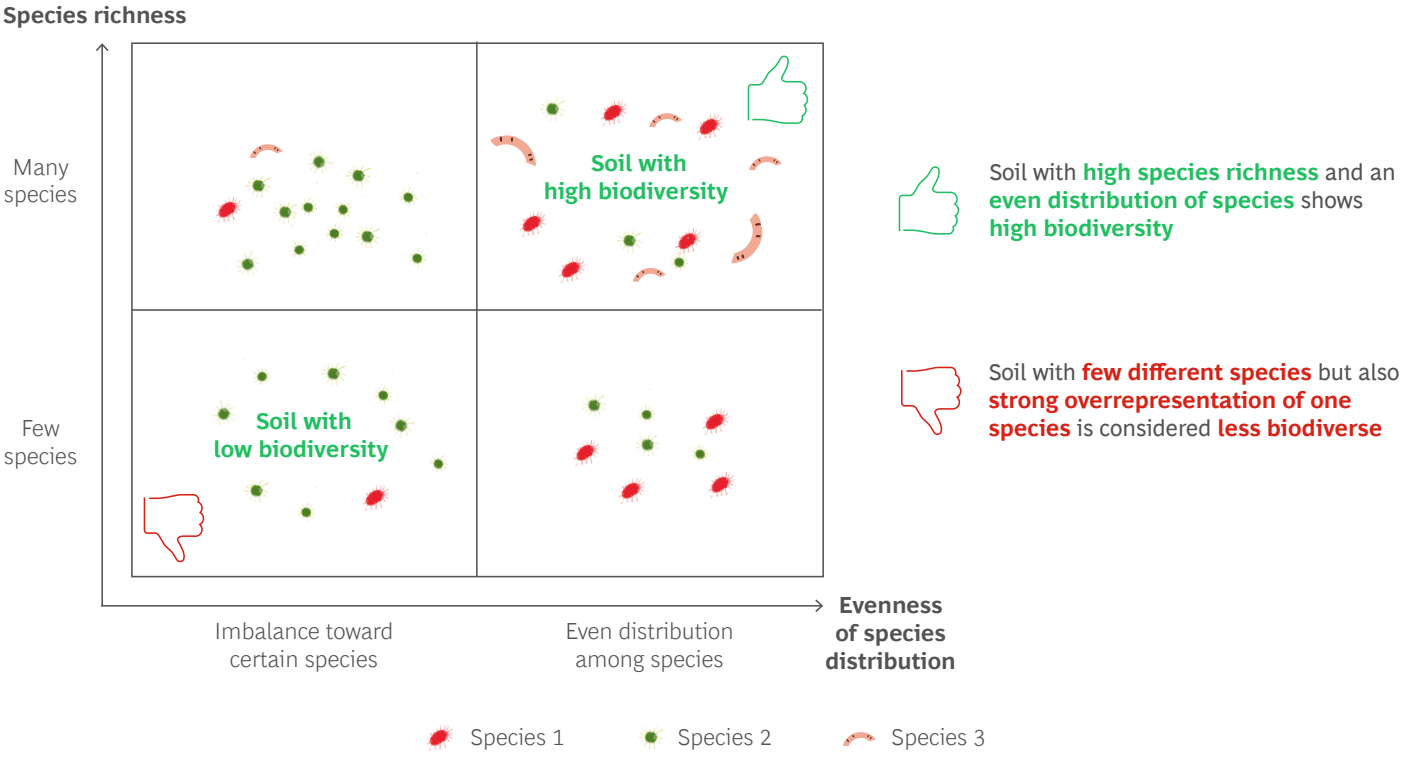
Soil's biodiversity is generally described through two main dimensions: richness of species and evenness of species distribution. Richness refers to the total number of different species within an ecosystem or sample, encompassing a wide variety of organisms that enhance the soil's functionality and adaptability to different environmental conditions. Evenness of distribution indicates how many different species there are in a given sample. This is expressed as ranging from 0 (most individual organisms belong to a single species) to 1 (the different individual species are evenly distributed).[12]

A sample with high biodiversity will contain many species with individuals evenly spread among them. Conversely, a sample dominated by a single species, even if it is abundant, would exhibit low biodiversity (**see Exhibit 6**).

Traditionally, analyzing soil microbiomes was labor-intensive and costly, requiring the manual counting of worms and springtails. Although this approach provides limited insights, failing to reflect the full extent of soil life, it still offers an initial indication of soil biodiversity, as there is a correlation between worm richness and overall soil biodiversity.

EXHIBIT 6

The Degree of Biodiversity in Soil Depends on Two Factors: Species Richness and Evenness of Species Distribution



Sources: C. Gardi and S. Jeffery, *Soil Biodiversity*, European Commission, 2009; BCG analysis.

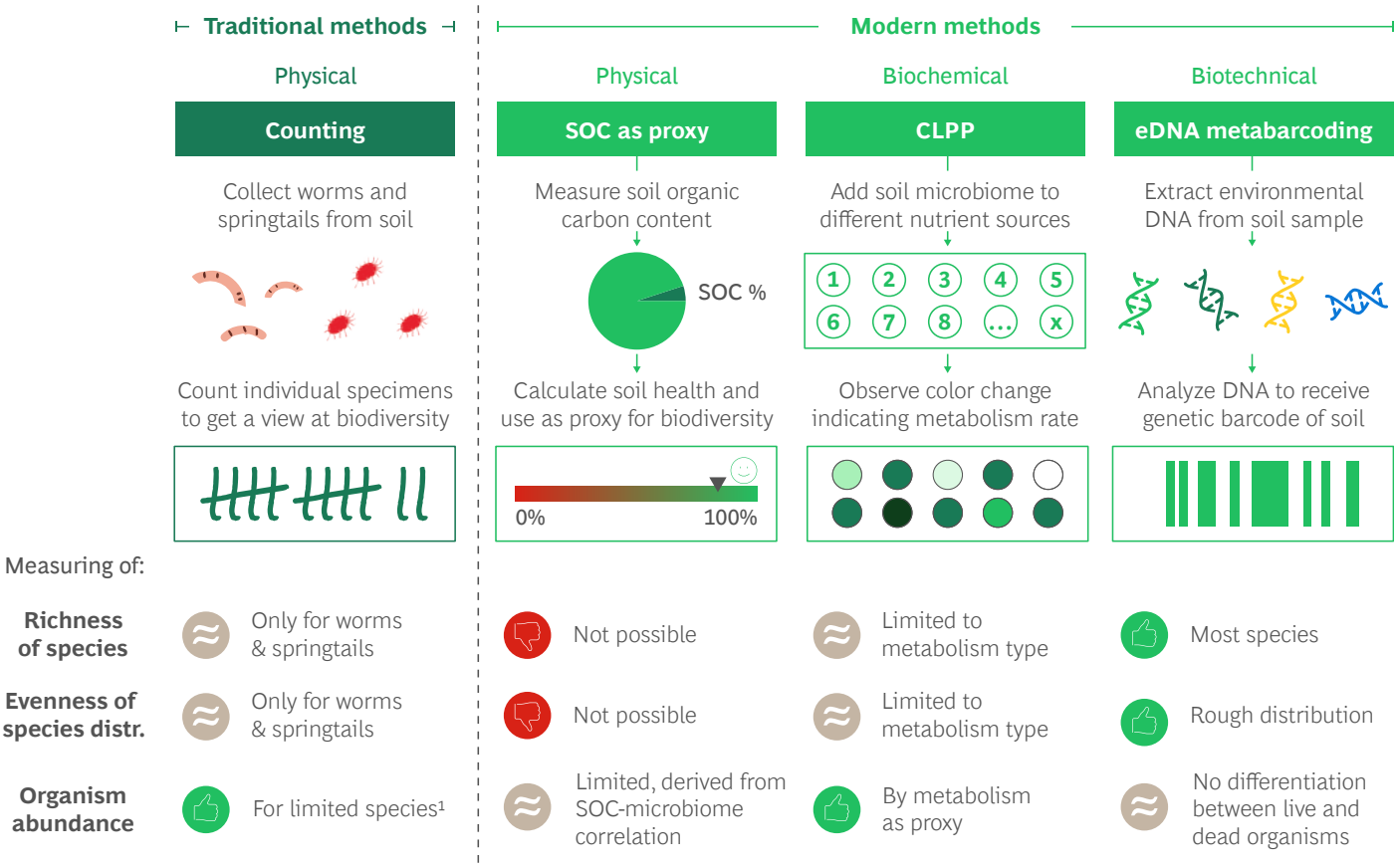
11. M. A. Anthony, S. F. Bender, and M. G. A. van der Heijden, "Enumerating Soil Biodiversity," *PNAS*, 2023.
12. C. Gardi and S. Jeffery, *Soil Biodiversity*, European Commission, 2009.

In recent years, technological advancements have added digital methods for measuring soil biodiversity and the potential for automating the process, thereby enabling more comprehensive and scalable assessments. These methods include measuring SOC as a proxy for biodiversity, community-level physiological profiling (CLPP), and environmental DNA (eDNA) metabarcoding **(see Exhibit 7)**.

- **Soil Organic Carbon.** SOC is a measure of carbon closely associated with SOM in the soil and can be analyzed using the Soil Health Assessment Protocol Evaluation tool, which leverages SOC as an indicator of biodiversity. This method is both cost-effective and easy to standardize, providing relevant insights into the overall abundance of organisms. However, it is a relatively simplified approximation and does not provide specific information on individual species or their functional diversity.

EXHIBIT 7

New Technologies Allow for More Accurate Measurement of Soil Biodiversity



Sources: NABU and BCG research; BCG analysis.
Note: CLPP = community-level physiological profiling.
[1]Respiration rate of whole sample can be measured, giving an indication of total microbiome abundance.

- **Community-Level Physiological Profiling.** CLPP measures functional biodiversity by assessing the ability of the soil's organisms to use various carbon and nitrogen sources, thus approximating the diversity of its organisms. Despite its limited use of equipment and great standardization potential, CLPP does not give detailed information on specific species. But it can add value by offering insights into the overall abundance of soil organisms and could complement the other new methods, as it is often readily available and could serve as a high-level indicator before more detailed tests are conducted.

- **Environmental DNA Metabarcoding.** eDNA metabarcoding is among the most advanced methods currently in use, and the standard method used in the LUCAS project, an EU-wide initiative measuring soil biodiversity begun in 2018. This method provides extensive information on the diversity of plant species and a wide array of organisms in soil by sequencing the soil microbiome's DNA but cannot differentiate between live and dead organisms. Still, eDNA metabarcoding has the highest potential as an accurate, standardized index of soil biodiversity, at comparably low cost. To be put to more common use, the method needs to be further standardized, made more cost-efficient, and scaled up. Significant progress in scaling DNA sequencing technology has already been made in the context of the COVID-19 pandemic, when such testing became mandatory and testing laboratories around the globe gained the capacity to sequence DNA. This capacity could potentially be used for stepping up soil testing while further reducing the cost.

Despite these advances, further progress is essential. While initial steps have been taken, including the establishment of the international Soil Biodiversity Observation Network (Soil BON) framework in 2021, aimed at improving biodiversity observations and related services, a complete biodiversity monitoring standard is yet to be developed. The EU's 2024 Soil Monitoring law aims to provide a more granular view of soil health, although it still requires more extensive data collection and standardization.

By scaling up new approaches and fostering healthy market competition between technological solutions, coupled with stringent public regulation of data, costs can potentially be dramatically reduced. This would significantly increase insights and drive efforts to enhance soil biodiversity, thereby mitigating soil, water, and air pollution. A healthy SOM is essential for all of soil's critical ecosystem functions and services—not just regulating water and sustaining healthy crops but even increasing the nutrient density of our food. In short, soil biodiversity must be considered a central aspect of the entire food value chain. (**See the sidebar "Elevating Soil Science in Agricultural Education."**)

Elevating Soil Science in Agricultural Education

The evolution of soil science is marked by key historical milestones. It began in 1755 with the humus theory, which suggested that plants derive their nutrition from humus, laying the foundation for soil science. In the 1970s, advances in microbial stoichiometry revealed the critical relationship between soil microorganisms and the formation of biomass. The 1980s introduced the aggregation theory, explaining the vital role of soil aggregates in the decomposition of organic matter.

However, early efforts to measure soil's biodiversity were hampered by inconsistent monitoring systems, lack of standardization, and varied methodologies. While aboveground indicators, like the EU common bird index, were established in the early 1980s, belowground biodiversity measurement techniques only began in 2018 with the LUCAS project, an EU-wide initiative measuring soil's biodiversity through eDNA barcoding. And it wasn't until 2024 that the EU passed the Soil Monitoring Law, mandating comprehensive soil assessments and structured evaluations.

Despite these theoretical and practical advances, there has been limited translation of soil science into practical agricultural education. Oftentimes, agricultural educational curriculums offer a limited scope and depths for soil science compared to other areas, such as plant health, agronomy, and genetics. This imbalance is also evident in graduation trends between 2013 and 2023, where the number of soil science graduates has increased by only 1% while the number of graduates in agricultural and crop sciences has surged by around 150%.

However, there are some promising signs of change. Regional agricultural chambers, such as Bavaria's, are starting to emphasize the importance of soil research, advocating for studies on erosion control, soil health, water management, and pest management. And leading agricultural companies are starting to invest in soil research by establishing dedicated soil research centers and advancing soil-related technologies.[1]

While these initiatives are promising, they remain in their infancy and lag behind the efforts made in aboveground agriculture. To fully harness the benefits of soil biodiversity for our ecosystem, it is imperative to accelerate research, education, and policy development in soil science.



1. Syngenta, "Feeding the Planet Should Not Cost the Earth," 2023, **https://www.syngenta.com/en/sustainability/soil-health**; Yara, "Yara Invests in Boomitra to Advance Soil Carbon Capture," press release, 2021, **https://www.yara.com/news-and-media/news/archive/2021/yara-invests-in-boomitra-to-advance-soil-carbon-capture/**.

The Economic Impact of Healthy Soil in Germany

As we have shown, a high degree of biodiversity is the key to productive soil, and healthy SOM is the key to biodiversity. Together, the benefits go beyond improving crop yields and reducing the need for synthetic fertilizers to include increased carbon capture, reduced emissions from synthetic fertilizers, less need for irrigation, and higher yield resilience during drought years. And as the amount and quality of SOM increases, so do those benefits.

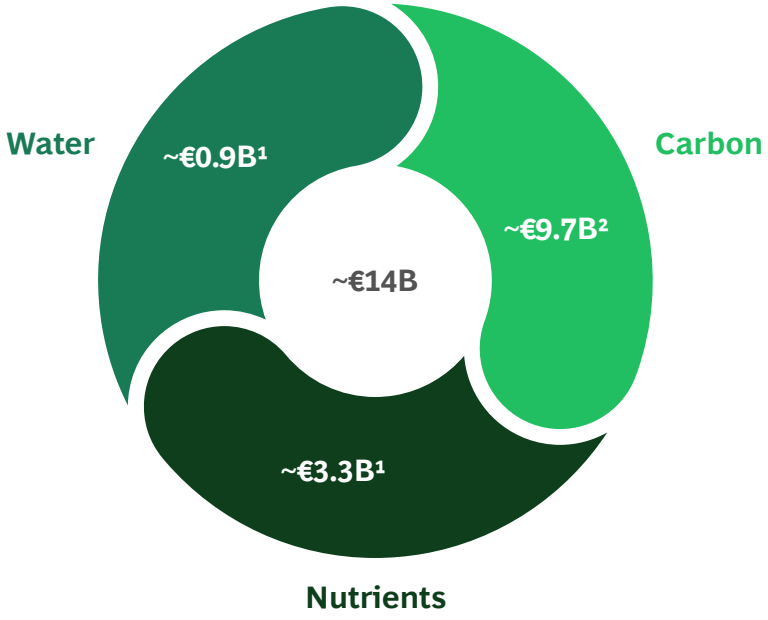
How much are these benefits worth? To quantify them, we used Germany as an example, since the nature of its soil is reasonably well understood. As such, it can serve as a stand-in for similar quantification efforts in other parts of the world; for example, the EU. **(See the sidebar "How the EU Could Benefit from Healthy Soil.")**

Our analysis shows that if Germany increased the amount of SOM across all its agricultural lands by around 1.3 tons per hectare per year—around 0.1 percentage point per year—in ten years, when the country's total SOM would increase by 1 percentage point, the potential economic benefits would total €14 billion annually **(see Exhibit 8)**.

The most significant economic impact is in the carbon dimension, with a potential benefit of approximately €9.7 billion in 2035, including €9.6 billion from enhanced carbon capture in soil and an additional €0.1 billion from decreased CO_2 emissions due to reduced fertilizer use. The nutrients dimension offers a benefit of about €3.3 billion, including €3.2 billion from improved crop yields and €0.1 billion from reduced need for synthetic fertilizers. The water dimension could provide a potential benefit of approximately €0.9 billion, including €0.7 billion from enhanced yield resilience during droughts, potentially increasing German wheat exports by around 12% (based on 2022 FAO data on German wheat exports) and €0.2 billion from reduced irrigation needs due to the soil's greater water-holding capacity.

EXHIBIT 8

Improved Soil Biodiversity Offers the Potential for €14 Billion in Annual Economic Benefit in Germany Alone



Sources: NABU; BCG analysis.
[1]Annual effect at 1 percentage point SOM increase, achieved after around ten years.
[2]€9.6 billion annual benefit effective from first year, €0.1 billion annual benefit effective at 1 percentage point SOM increase, achieved after around ten years.

How the EU Could Benefit from Healthy Soil

While we haven't conducted an in-depth analysis of the benefits of healthy soil across the EU, it is possible to estimate the potential effects of increased SOM on carbon capture, reduced emissions from synthetic fertilizers, less need for irrigation, and higher yield resilience during drought years in the region, and its economic value. This can be done by extrapolating the results of the analysis focused on Germany to the entire EU region, thanks to the relatively similar agricultural conditions there.

A comparison of the two areas shows just how similar they are in terms of amount and type of agricultural land and how it is used. Of Germany's 15.5 million hectares used for agriculture, 75%, or 11.4 million hectares, is cropland and 25%, or 3.9 million, is pastureland (the rest is peatland, which does not figure in our analysis). These proportions are very similar to the EU as a whole, where around 70% (or 111 million hectares) is cropland and around 30% (or 52 million hectares) is pastureland.

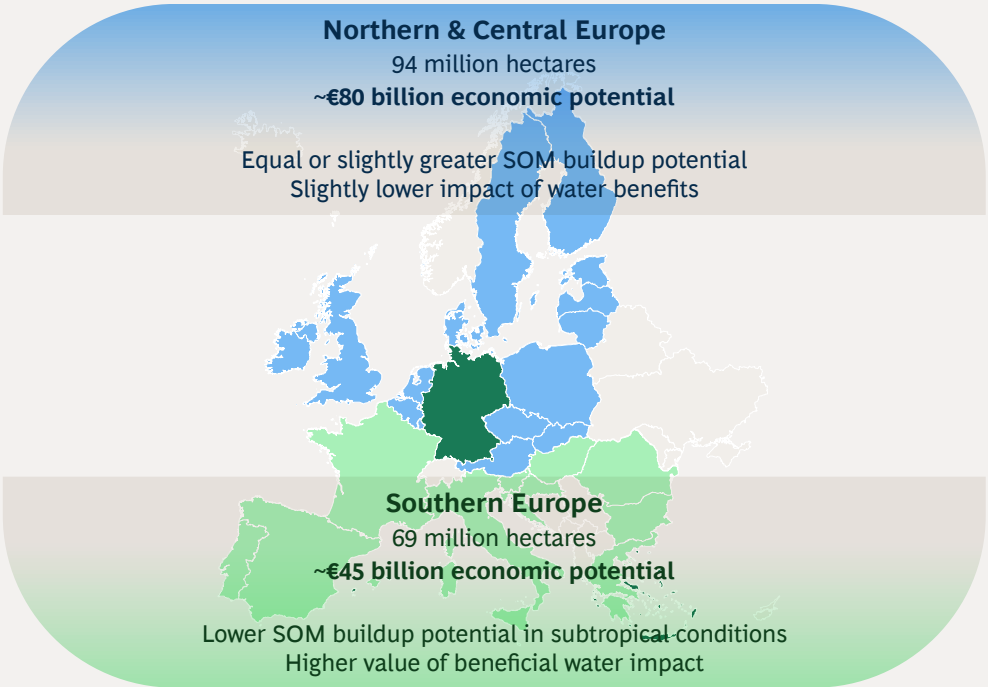
All of the EU's agricultural land is governed under the region's Common Agriculture Policy, so we can assume that similar conditions and practices take place across the region.

The benefits of healthier soil, and thus in the economic value, however, depend on differences in Europe's climate patterns and soil types, which vary between the north and the south. Central and northern European countries are similar to those in Germany, so the potential for SOM buildup is similar—as is the value of the positive effects in terms of water scarcity and the cost of water.

In contrast, southern Europe's subtropical climatic conditions foster a higher rate of microbial respiration in the winter, and thus less net SOM buildup over the annual crop cycle. As a result, we estimate that the potential for carbon sequestration is between 65% and 75% of that in the more moderate countries in northern Europe. On the other hand, the economic benefit of healthy soil's improved ability to hold and filter water is higher in the south, as the climate in many Mediterranean cropping regions is drier and the cost of water is higher.

All in all, we estimate the economic potential of healthy soil in Europe to be between €120 billion and €130 billion annually (**see the exhibit**).

Healthy Soil Practices Across the EU could Lead to Economic Benefits of €120 Billion to €130 Billion Annually



Sources: Food and Agriculture Organization of the United Nations; European Environment Agency; BCG analysis.

These economic benefits are based on Germany's 15.5 million hectares of agricultural land, which consists of roughly 11 million hectares of cropland and 4 million hectares of grassland.[13] (**See the sidebar "Land Use in Germany."**) Altogether, the benefits equal about €1,000 per hectare per year. We believe that other countries and agricultural regions of similar structure in temperate climates would receive similar economic benefits from comparable increases in SOM.

In subtropical and tropical regions, however, the buildup potential of SOM is lower given increased microbial respiration, especially in their mild winters. So the potential for building up SOM is slightly smaller than in moderate climates, as are the economic benefits. Yet every region can benefit from increased soil health.

The following sections describe in detail the economic benefits of increased SOM in each of the carbon, nutrient, and water dimensions, and how these benefits are calculated. (**See the appendix for additional technical details on the variables and sources of this analysis.**)

Carbon

Soils hold a vast amount of carbon—more than the atmosphere and all the world's plants and forests combined. More than two-thirds of the organic carbon stored in terrestrial ecosystems resides in SOM, 58% of which is stored carbon. This means that one ton of SOM holds about 0.58 tons of carbon.[14] Even minor changes in the balance between carbon inputs of new biomass from plant residues and the release and evaporation of carbon into the atmosphere due to poor agricultural practices can substantially increase atmospheric CO_2 levels. Stabilizing the carbon in soil through agricultural practices such as no-till farming, which minimizes the release of carbon, and the use of cover crops, which sequesters more carbon in the soil, has become crucial in recent years due to its positive impact on atmospheric chemistry.

Increasing the amount of SOM in Germany's agricultural lands can have a dual impact on the country's carbon footprint. First, agricultural soils hold immense potential as carbon sinks, capturing and storing carbon in the form of SOM. However, carbon storage is sensitive to both soil and environmental conditions: Optimal pH levels, balanced water content, and avoiding extreme dryness are essential to maintaining efficient carbon capture.

Second, increasing SOM reduces the need for chemical fertilizers, thereby lowering overall greenhouse gas (GHG) emissions, since synthetic fertilizer production is a very carbon-intense industrial process. Healthier soils have a higher nutrient-holding capacity while also allowing crops to uptake nutrients more efficiently. Therefore, healthier soils enable stable crop yields with less fertilization.

Increasing the amount and health of Germany's SOM would help the EU reach its goal of cutting GHG emissions by 55% in 2030 and to net zero by 2050.[15] Germany emitted approximately 670 million tons of greenhouse gases in 2023,[16] and we calculate that an increase in SOM could reduce these emissions by 6% annually.

Quantification Approach. We estimate the overall annual economic value of the benefits of an increase in SOM share by 1 percentage point over ten years from increased carbon sequestration and carbon emissions at approximately €9.7 billion. To arrive at this estimate, we assumed an optimal balance of the six belowground factors contributing to high-quality, healthy SOM. We excluded the variability in SOM buildup depending on soil type due to the complex interrelations between soil types and SOM, and the limited available research data.

The total economic benefit includes:

- **Approximately €9.6 billion annually from increased carbon capture** will accrue from year 1, since every annual increase in SOM of 1.3 tons per hectare will sequester approximately 2 tons of carbon. The impact of SOM on increased carbon capture was determined by multiplying the annual SOM buildup by CO_2 equivalents and associated costs. Unlike the analysis of nutrients and water that follows, this analysis covers both Germany's cropland and grassland area. Increasing the soil's ability to capture carbon requires the continuous buildup of SOM, and thus requires an ongoing, sustained shift to appropriate agronomic practices.
- **Approximately €0.1 billion annually** will be realized from reductions in fertilizer use.

13. Destatis, "Floor Area Total According to Types of Use In Germany," **https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Agriculture-Forestry-Fisheries/Land-Use/Tables/areas-new.html**.
14. J. Six et al., "Bacterial and Fungal Contributions to Carbon Sequestration in Agroecosystems," *Soil Science Society of America Journal*, March 2006.
15. European Parliament, "Reducing Carbon Emissions: EU Targets and Policies," EU Monitor, October 30, 2023.
16. Umwelt Bundesamt, "Indicator: Greenhouse Gas Emissions," 2023, **https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-greenhouse-gas-emissions#at-a-glance**.

Land Use in Germany

To better understand the benefits of improving Germany's soil, it's important to consider the addressable surface area for this study. Approximately 46% of Germany's land is dedicated to agriculture, amounting to 16.3 million hectares. According to the UN's Food and Agriculture Organization, "agricultural land includes areas that are arable, under permanent crops, or used for permanent pastures. This also covers land under temporary crops (counting double-cropped areas once), temporary meadows for mowing or grazing, market or kitchen gardens, and temporarily fallow land."[1]

The remaining 54% of the land in Germany consists of 31% forest, 14% settlements, industry, and transportation, 4% other agricultural land including buildings and yards, 3% various types of vegetation, and 2% bodies of water.[2]

For the purposes of this study, we focused on 15.5 million hectares of agricultural land. This includes 11.4 million hectares of cropland and 4.1 million hectares of grassland. It does not include Germany's 0.8 million hectares of peatland, which should not be used as agricultural land due to its significant carbon storage capacity and climate functions



1. FAO, "Agricultural Land," **https://www.destatis.de/EN/Themes/Countries-Regions/International-Statistics/Glossary/AgriculturalLand_c.html**.
2. Destatis, "Floor Area Total According to Types of Use In Germany," **https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Agriculture-Forestry-Fisheries/Land-Use/Tables/areas-new.html**.

Sensitivity Analysis for Carbon Capture. Our overall estimated economic benefit of €9.6 billion assumes a moderate SOM buildup of 1.3 tons per hectare per year and uses the price for external climate costs at €223 per ton. However, the calculated impacts for both increased carbon capture and reduced carbon emissions from the decreased need for fertilizer will vary depending on the amount of annual SOM buildup and variations in the price of carbon:

- **Low SOM Buildup.** 0.8 tons per hectare per year.
- **Moderate SOM Buildup.** 1.3 tons per hectare per year.
- **High SOM Buildup.** 2.9 tons per hectare per year.

To assess the economic value of increased SOM, three different price scenarios per ton of CO_2 equivalent (CO_2e) projected for 2035 were used:

- **Price of Carbon Certificates in Voluntary Markets.** Based on consensus estimates and expert judgments, around €55 per ton.
- **Price of Carbon Certificates in Mandatory Markets.** Based on the forward price on the European Trading System (ETS), around €157 per ton.
- **External Climate Costs.** The total societal costs of carbon, around €223 per ton.

Our analysis of these figures shows that the annual economic benefit from increased carbon capture could vary from €1.5 billion to €21.4 billion (**see Exhibit 9**).

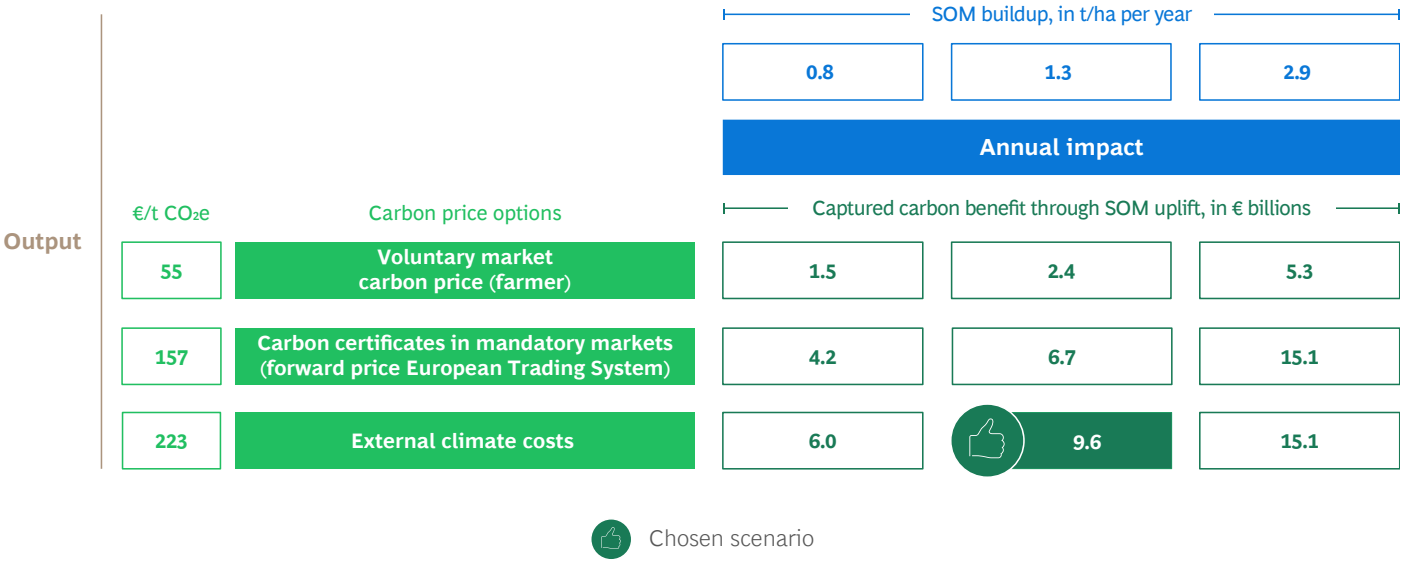
Nutrients

With the global population set to approach 10 billion by 2050, increasing the available food supply is becoming critical. Yet the surge in demand is coming at a time when agricultural land is rapidly diminishing; every year, for example, Germany alone loses around 25,000 hectares of farm- and forestland to urban development.[17] Thus, preserving and enhancing soil health on remaining agricultural land has never been more crucial.

Healthy SOM can boost both crop yields and the nutritional value of food. The quality of SOM is best approximated by the amount of SOC, which is closely linked to the availability of nutrients in the soil and improved soil moisture levels—and consequently to crop growth and yields. Research indicates that increasing SOC by 1 percentage point can boost average crop yields by around 11% for maize (corn) and around 26% for wheat, while simultaneously reducing the need for fertilizers by around 8% for maize and 6% for wheat.[18]

EXHIBIT 9

The Economic Impact of Greater Carbon Capture Depends on Increases in SOM and the Price of Carbon



Sources: NABU analysis.
Note: CO_2e = CO_2 equivalent; t/ha = tons per hectare.

17. Umwelt Bundesamt, "Ten Million Hectares of Arable Land Worldwide Are 'Lost' Every Year," press release, 2015.
18. E. E. Oldfield, M. A. Bradford, and S. A. Wood, "Global Meta-Analysis of the Relationship Between Soil Organic Matter and Crop Yields," *SOIL*, 2019.

The correlation between SOM, yield increases, and fertilizer reduction is not linear, however. Beyond a 1 percentage point increase in the proportion of SOM, the effects on yield uplift and fertilizer reduction diminish.

The benefits of increased SOM on crop yields and reduced fertilizer needs also depend on soil type, the quantity of microorganisms and biomass, and pH levels. For instance, soils with higher clay and silt content contain more minerals that can retain nutrients and water, enhancing SOM formation compared to sandy soils, which have lower SOM-building capacity. Furthermore, adding soil boosters such as earthworms and beneficial microorganisms can also enhance crops' nutrient uptake, thereby increasing biomass by up to 23%.[19] Greater biodiversity matters, too; in one example, soils containing a limited range of microorganisms reduced yields by 13%, nitrogen uptake by 20%, and phosphorus uptake by 58% compared with more biodiverse soils.[20]

Healthy SOM can also improve the nutrient quality of food and increase independence from food imports. Research shows that crops from healthy soils with high biodiversity have a higher nutrient density, including a higher level of omega-3 fats and minerals, making soil biodiversity a significant contributor to public health. And by increasing yields, soils with a healthy, biodiverse SOM can reduce dependency on food imports. (**See the sidebar "Food, Health, and Soil Biodiversity."**)

> Crops from healthy soils with high biodiversity have a higher nutrient density, making soil biodiversity a significant contributor to public health. And by increasing yields, such soils can reduce dependency on food imports.

Quantification Approach. As above, in analyzing the economic value of increased nutrients, we assumed an optimal balance of the six belowground factors contributing to high-quality, healthy SOM. We did not take into account the additional variability in SOM buildup depending on soil type, due to the complex interrelations between soil types and SOM and the limited available research data.

Our analysis shows that a 1 percentage point increase in SOM share (which would take approximately 10 years) could yield an annual benefit of around €3.3 billion. This includes:

- **Approximately €3.2 Billion from Increases in Yields.** This assumes that as the share of SOM increases over time, the boost to yields will decrease. Compared to global meta-analysis research,[21] we took a more conservative perspective and assumed yield increases of around 9% for maize and 20% for wheat, with a SOM increase of 1pp, while scaling up the results to other crops.

- **Approximately €0.1 Billion from Reduced Need for Fertilizer.** Compared to global meta-analysis research,[22] we took a more conservative approach and assumed fertilizer reductions of 6% for maize and 4% for wheat, with a 1 percentage point SOM increase, while scaling up the results to other crops.

The increase in yields was calculated by multiplying crop price, yields, crop area, and assumed yield increase factors. To apply the yield increase factors across crops, we used average values based on the results for maize (around 9% increase in yield) and wheat (around 20% yield increase), and applied further conservative assumptions when scaling up the results to other crops in Germany.

Sensitivity Analysis. For sensitivities, we evaluated two main variables in assessing the estimated economic effect of improved nutrients in the soil: the price level for crops and the assumed yield increases. Depending on these two parameters, the economic benefits ranged from €1.4 billion to €6.5 billion (**see Exhibit 10**).

Price level for crops:

- **Lower Range.** Price index as of 2020 levels.

- **Midrange.** 2024 average prices.

- **Upper Range.** Price index forecasted to 2035 based on the average inflation rate over the past five years.

Yield increases:

- **Lower Range.** Approximately 9% yield increase across crops, applying the value from maize, the least affected crop, to all crops.

- **Midrange.** Approximately 15% yield increase based on detailed assessment per crop.

- **Upper Range.** Approximately 20% yield increase, applying the value for wheat, the most affected crop, to all crops.

19. J. W van Groenigen et al., "Earthworms Increase Plant Production: A Meta-Analysis," *Scientific Reports*, 2014.
20. S. F. Bender et al., "Impoverished Soil Life Reduces Nutrient Efficiency and Increases Environmental Pollution," Swiss Agricultural Research, 2023.
21. E. E. Oldfield, M. A. Bradford, and S. A. Wood, "Global Meta-Analysis of the Relationship Between Soil Organic Matter and Crop Yields," *SOIL*, 2019.
22. E. E. Oldfield, M. A. Bradford, and S. A. Wood, "Global Meta-Analysis of the Relationship Between Soil Organic Matter and Crop Yields," *SOIL*, 2019.

Food, Health, and Soil Biodiversity

Globally, over 3 billion people cannot afford a healthy diet, and 8.6% of people in the EU struggle to afford adequate meals regularly.[1] Besides food insecurity, rising rates of overweight, obesity, and diet-related noncommunicable diseases (NCDs), such as heart disease, diabetes, and cancer, cost each EU citizen more than €411 annually.[2]

Medical science increasingly recognizes the link between healthy soil microbiomes, nutrient quality, and NCDs. Consuming crops grown in biodiverse soil introduces a variety of beneficial microbes into the human diet, which support gut health and possess anti-inflammatory properties. Studies indicate, for example, that greater microbial diversity can enhance the body's ability to combat allergies.[3]

Soil biodiversity also significantly enhances the nutritional value of food. The diverse microorganisms in healthy soil contribute to the growth of nutrient-rich crops, which are essential for a balanced diet. A diverse soil microbiome also leads to a more biodiverse aboveground ecosystem. Human health thrives on a diverse diet of fruits and vegetables, and this diversity starts with the soil in which our crops are grown.

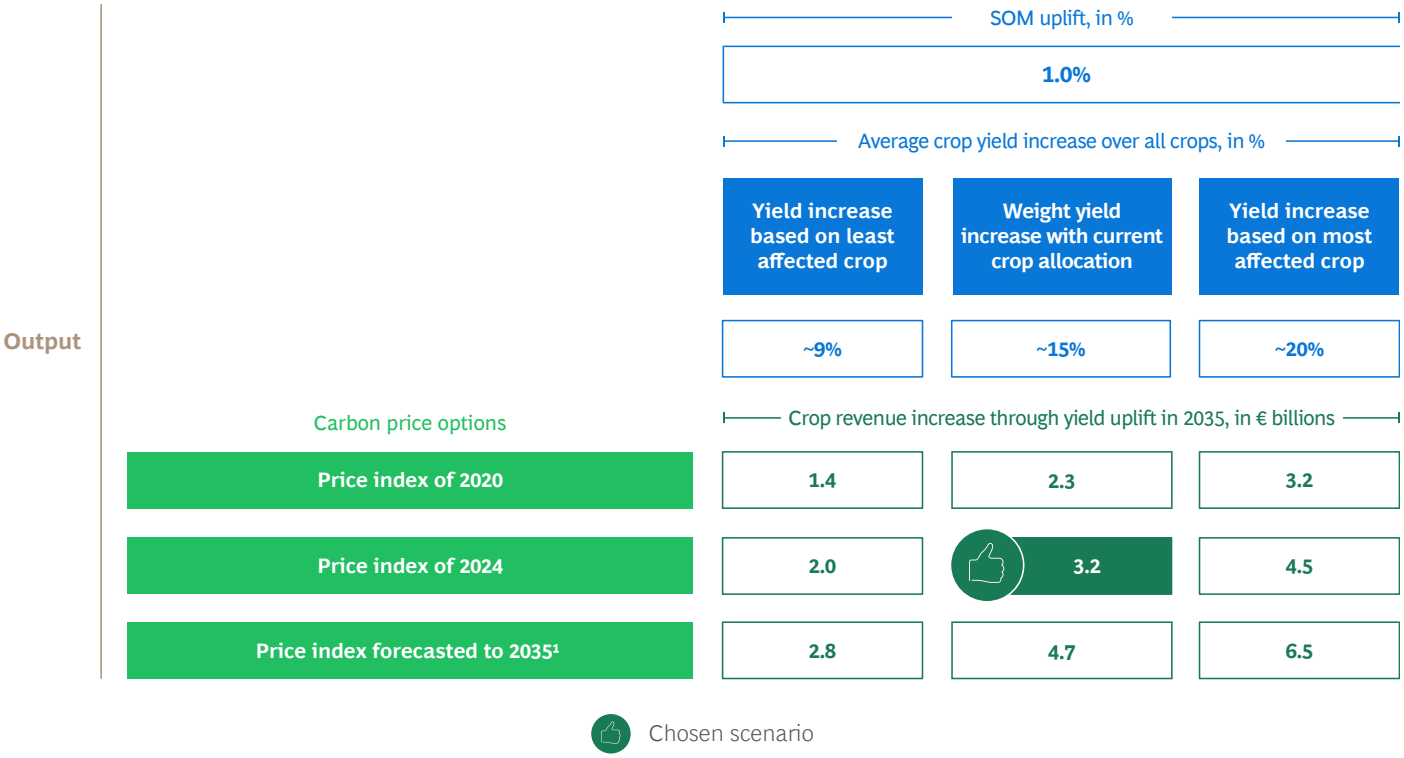
Maintaining healthy soil biodiversity is crucial for food security and public health, fostering better nutrition, and reducing the prevalence of diet-related and inflammatory diseases.



1. Eurostat, "8.6% of People in the EU Unable to Afford Proper Meal," 2023, **https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220225-1**.
2. European Commission, "Cost of Non-Communicable Diseases in the EU," 2024.
3. A. Riiser, "The Human Microbiome, Asthma, and Allergy," *Allergy and Asthma and Clinical Immunology* 11, no. 35 (2015); A. C. Aguilera, I. A. Dagher, and K. M. Kloepfer, "Role of the Microbiome in Allergic Disease Development," *Current Allergy and Asthma Reports,* 2020.

EXHIBIT 10

The Economic Impact of Greater Crop Yields Depends on Size of Yield Increase of Crops and their Market



Source: NABU analysis.
Note: t/ha = tons per hectare.
[1]Based on price increase over the past five years.

The economic value of the reduction in fertilizer need was calculated by multiplying the price of fertilizer, the fertilizer requirement for crops, and the crop area by the assumed amount of fertilizer reduction. This was done separately for the three main crop nutrients: nitrogen, phosphorus, and potassium. The total fertilizer cost benefits were calculated using the following prices: €1.06 per kilogram for nitrogen, €0.90 per kilogram for phosphorus, and €0.80 per kilogram for potassium. We assumed a decrease in required fertilizer use of 6% for maize and 4% for wheat. Using the same logic we used to calculate the increase in yields, we scaled the results for both maize and wheat to the overall effects for Germany by using averages and applying further conservative assumptions.

Water

As climate change advances, the need for irrigation is set to skyrocket, with global cropland likely to require four times more water over the next 12 years.[23] In fact, Germany is already experiencing more frequent and severe droughts. Enhancing the soil's ability to retain water—known as its available water holding capacity (AWHC)—can significantly alleviate the strain on groundwater sources and ensure robust crop yields even during dry periods. The economic benefits include increased crop yields and the reduced need for irrigation.

23. L. Rosa et al., "Potential for Sustainable Irrigation Expansion in a 3 °C Warmer Climate," *PNAS*, 2020.

One primary driver for increased AWHC is SOM. A 1 percentage point increase in the amount of SOM improves AWHC by at least 1.5%[24] and thus enhances the amount of water available to crops. This impact is highly dependent on soil type, particularly its bulk density, degree of compaction, and mineral content. Soils with lower bulk density and less compaction have more pores to store water, and thus an increased AWHC, while a high share of minerals also increases AWHC. A 100-gram sample of silty loam soil with 1 gram of SOM, for example, can contain 19% water, compared with just 15% for sandy soils.[25]

Soils containing more SOM and thus more available water contribute to greater yield resilience during drought. Healthy, biodiverse SOM also contributes to greater plant growth and deeper roots and helps protect against erosion. By mitigating soil erosion—the removal of the topsoil layer through water and wind—the EU could avoid annual losses of €1.25 billion in agricultural productivity.[26] Greater AWHC also reduces flooding risk. Healthy soil provides enhanced water filtration through the role of organisms in reducing soil compaction and additional SOM layers. As an added benefit, healthy, biodiverse SOM may contain microorganisms that improve plant resilience in dry conditions, such as the fungus *M. alpine*, which has been shown to improve wheat's tolerance to drought.

Quantification Approach. As above, we assume an optimal balance of the six belowground factors contributing to high-quality, healthy SOM. Our analysis shows that a 1 percentage point increase in SOM share after ten years could yield annual water-related benefits of around €0.9 billion:

- **Approximately €0.7 Billion from Increased Yield Resilience During Drought.** The impact of increased SOM on greater yield resilience was calculated by multiplying the assumed yield resilience factor by the estimated yield reductions due to drought.
- **Approximately €0.2 Billion from Saved Irrigation Costs.** The impact of more SOM in reducing irrigation costs was calculated by multiplying increases in AWHC driven by more SOM with the area of irrigated cropland and the price of water.

Our analysis of the increase in yield resilience as the result of increased AWHC focuses on two main factors: the assumed resilience factor due to increased SOM and the average losses in yield when conditions are dry. For the yield resilience, we assumed that a 1 percentage point increase in SOM would reduce the decline in yields by 25% during dry conditions. This effect is not linear, however; as the share of SOM increases over time, the impact on yield resilience slows.

The effect of dry conditions on yield was assessed based on reduced yields during the drought year of 2018.

Sensitivity Analysis. We evaluated two main variables in determining the impact of greater AWHC on yield resilience: the assumed resilience factor due to increased SOM and the average losses in yields due to dry conditions (**see Exhibit 11**).

Resilience factor:

- **Lower Range.** 20% increased yield resilience, as assumed in our last study on regenerative agriculture.
- **Midrange.** 25% increased yield resilience, as per assumptions from our expert network and conducted farmer panels.
- **Upper Range.** 35% increased yield resilience, the maximum yield resilience observed in selected crops.

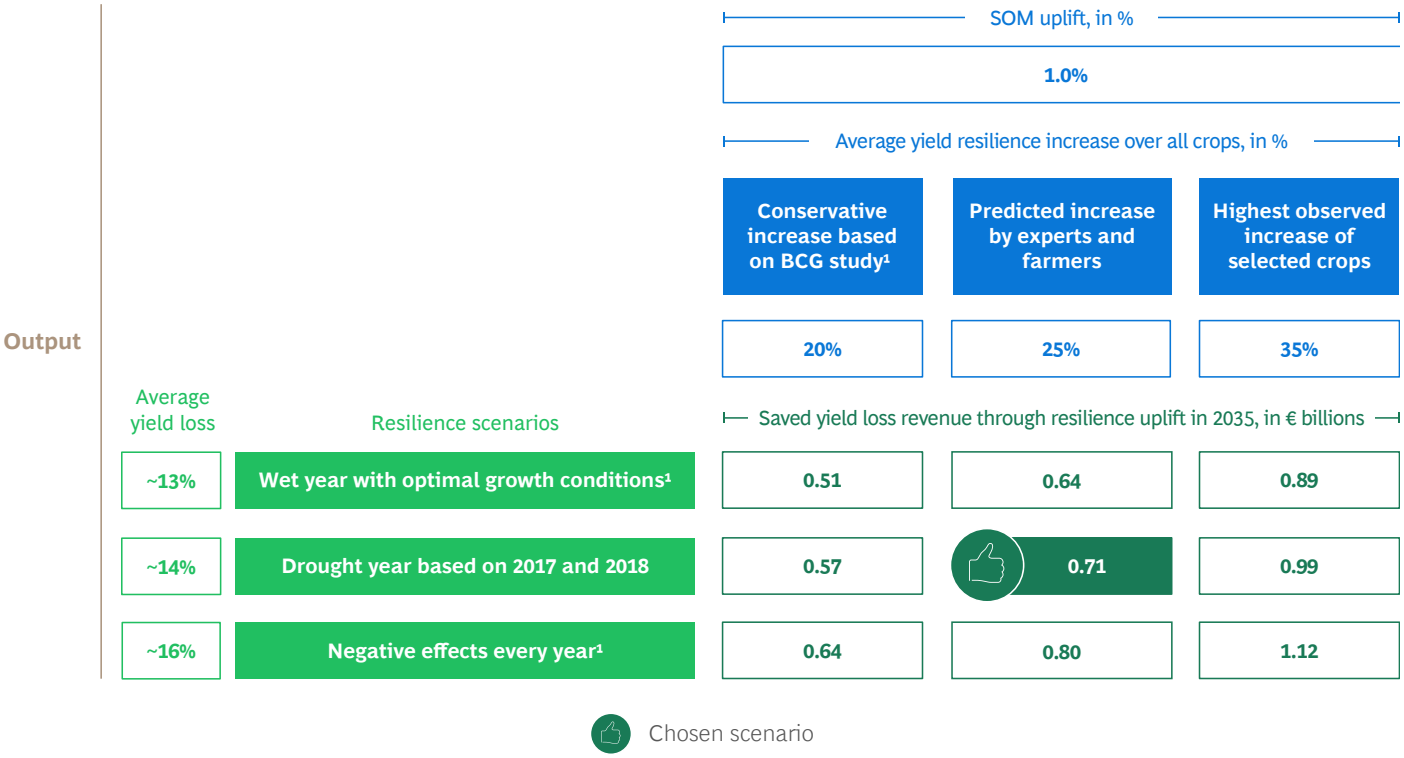
Average yield losses:

- **Lower Range.** Approximately 13% average yield losses based on our regenerative agriculture study, assuming selected particularly wet years with optimal growth conditions.
- **Midrange.** Approximately 14% average yield losses based on a detailed comparison of yield data for 2017, a non-drought year, and 2018, a drought year.
- **Upper Range.** Approximately 16% average yield losses based on assumed worsening of climate conditions and increased severity of droughts.

24. Z. Libohova et al., "Reevaluating the Effects of Soil Organic Matter and Other Properties on Available Water-Holding Capacity Using the National Cooperative Soil Survey Characterization Database," *Journal of Soil and Water Conservation*, 2018.
25. Z. Libohova et al., "Reevaluating the Effects of Soil Organic Matter and Other Properties on Available Water-Holding Capacity Using the National Cooperative Soil Survey Characterization Database," *Journal of Soil and Water Conservation*, 2018.
26. P. Panagos et al., "Cost of Agricultural Productivity Loss Due to Soil Erosion in the European Union: From Direct Cost Evaluation Approaches to the Use of Macroeconomic Models," *Land Degradation & Development*, March 2018.

EXHIBIT 11

The Economic Impact of Greater Yield Resilience Depends on Assumed Yield Resilience Factors and Average Yield Losses Due to Droughts



Source: NABU analysis.
[1]T. Kurth et al., *The Case for Regenerative Agriculture in Germany—and Beyond*, BCG, 2023.

Our estimate of the economic benefits of reduced irrigation as a result of greater water retention assumes a 1 percentage point SOM share buildup, an increased AWHC of around 60,000 liters per hectare, 2 million hectares of irrigated land (assumed in 2035), and a price of €1.56 per cubic meter of water.

To assess sensitivities, we evaluated two key variables in determining the economic impact of reductions in required irrigation in Germany: the sensitivity of AWHC to increases in SOM and the price of water **(see Exhibit 12)**.

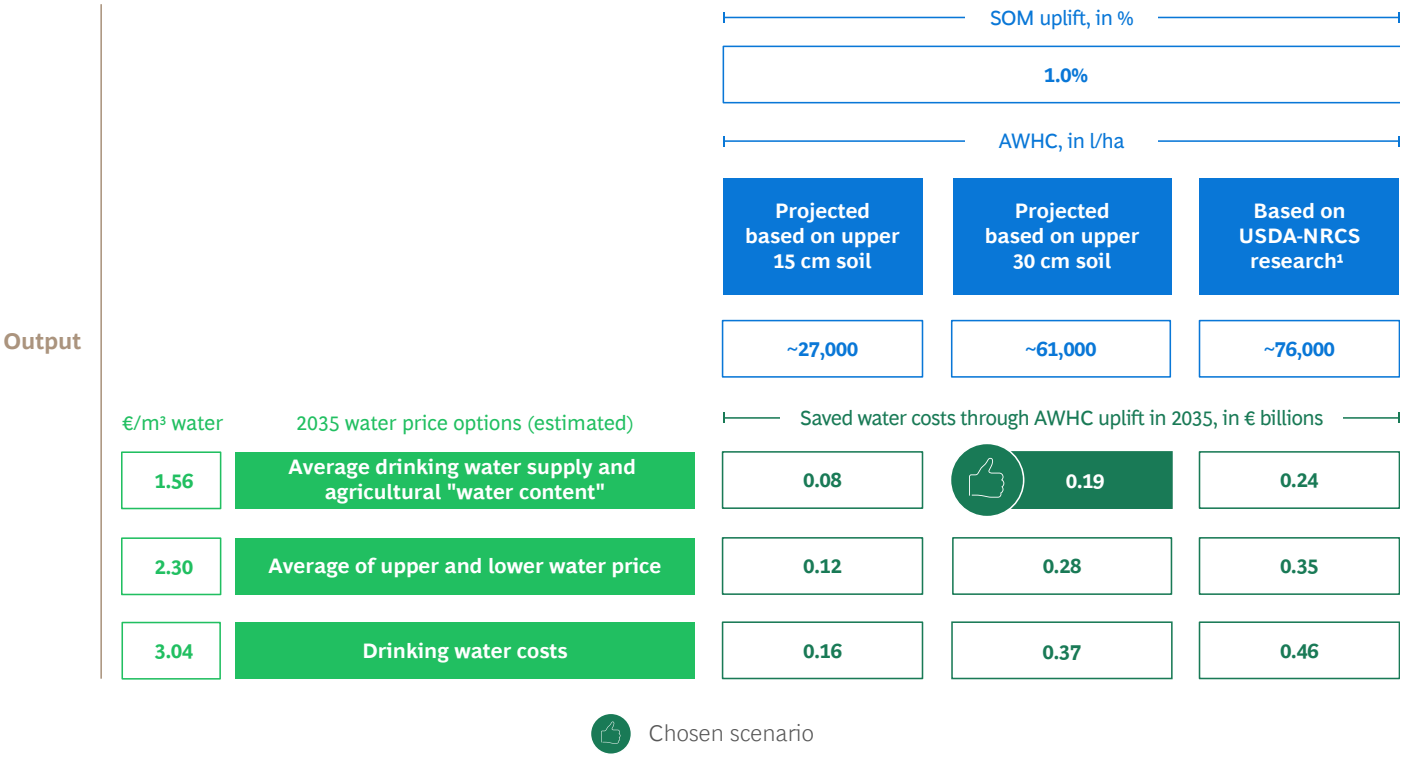
AWHC at 1 percentage point SOM increase:

- **Lower Range.** Approximately 27,000 liters per hectare increased AWHC, based on available water in the upper 15 centimeters of soil.[27]
- **Midrange.** Approximately 61,000 liters per hectare increased AWHC, based on available water in the upper 30 centimeters of soil.[28]
- **Upper Range.** Approximately 76,000 liters per hectare increased AWHC, based on USDA-NRCS research.[29]

27. Z. Libohova et al., "Reevaluating the Effects of Soil Organic Matter and Other Properties on Available Water-Holding Capacity Using the National Cooperative Soil Survey Characterization Database," *Journal of Soil and Water Conservation*, 2018.
28. Z. Libohova et al., "Reevaluating the Effects of Soil Organic Matter and Other Properties on Available Water-Holding Capacity Using the National Cooperative Soil Survey Characterization Database," *Journal of Soil and Water Conservation*, 2018.
29. J. Bhadha et al., "Raising Soil Organic Matter Content to Improve Water Holding Capacity," *EDIS*. 2017.

EXHIBIT 12

The Economic Impact of Greater Water Retention on the Cost of Irrigation Depends on Increased AWHC and the Cost of Water



Sources: NABU; BCG analysis.
Note: AWHC = available water holding capacity; t/ha = tons per hectare.
[1]J. Bhadha et al., "Raising Soil Organic Matter Content to Improve Water Holding Capacity," 2017.

Price of water:

- **Lower range.** Average of the cost of drinking water and the cost of water incurred by farmers in 2035 (a projected €1.56/cubic meter).
- **Average.** Average of the upper and lower water price range in 2035 (a projected €2.30/cubic meter).
- **Upper range.** Price of drinking water paid by consumers in 2035 (a projected €3.04/cubic meter).

While the economic value of reduced irrigation in Germany—around €0.2 billion—may seem comparatively low, that value would become much more significant when looking at other European countries. In Spain, for example, the economic potential is approximately €1.0 billion, five times the potential in Germany. (This assumes around 5 million hectares of irrigated land (20% above current levels), AWHC of 60,000 liters per hectare, and a less conservative price of €3.04/cubic meter due to the likelihood that water in Spain will be more scarce in 2035 than it is now.)

Benefits of healthy soill include increased carbon capture, reduced emissions from synthetic fertilizers, less need for irrigation, and higher yield resilience during drought years.





A Blueprint for Healthy Soil

Like most nations around the world, Germany is lagging in environmental sustainability. According to the country's Federal Ministry for the Environment, Nature Conservation, Nuclear Safety, and Consumer Protection, it had exceeded six of the nine planetary boundaries in 2023—climate change, biosphere integrity, nitrogen and phosphorus loss, land use change, freshwater reserves, and pollution from novel substances. These pressing environmental threats are prompting the country's policymakers to reassess and broaden their focus areas.

One significant step has been taken under the European Green Deal, which aims to address these challenges. It strives to achieve net-zero emissions by 2050 and encompasses some regulations affecting the soil, such as the EU soil strategy for 2030, the EU Soil Monitoring Law, and the Nature Restoration Law. These regulations aim to establish standardized soil monitoring systems; improve soil quality and biodiversity by promoting sustainable land use practices, for example; and restore degraded ecosystems such as dried-up peatland.

It is crucial for Germany to develop an integrated soil management strategy to drive significant improvements in soil biodiversity. This strategy should unite various stakeholders—academia, the agricultural industry, agricultural state institutes, and farmers—while emphasizing the interdependencies between the aboveground and belowground factors that influence soil biodiversity.

To further emphasize the importance of soil health, three critical measures must be prioritized: better research and data, greater action across the entire soil value chain, and policies and incentives to further promote soil biodiversity practices.

Research and Data. Defining and implementing standardized measurement tools for soil biodiversity is crucial. Currently, there is a lack of standardized methods to assess soil condition, health, and biodiversity within Germany and across Europe. Among the four primary soil measurement techniques—counting earthworms, using the share of SOC as a proxy, CLPP, and eDNA metabarcoding—the latter offers the deepest insights into species richness and evenness of distribution, the two critical factors for soil biodiversity. While high costs and scalability issues have limited its widespread adoption, the DNA sequencing capabilities developed in response to the COVID-19 pandemic could make eDNA metabarcoding more available.

In the meantime, combining other soil measurement techniques could serve as a bridging solution. For instance, SOC as a proxy could be combined with CLPP to measure soil biodiversity. SOC as proxy gives only limited insights into actual soil biodiversity, serving more as an indication than an exact measure of species richness and evenness of species distribution. Despite its limitations, however, SOC is a highly scalable method with the potential for automation. When combined with CLPP, which offers deep insights into functional soil biodiversity but is less scalable, this method provides a more accurate approximation of soil biodiversity. SOC as a proxy can be implemented quickly across Germany and the EU, while CLPP could then be used selectively in areas where SOC results indicate potential problems.

In the meantime, eDNA metabarcoding can be established, potentially by making use of the testing technology similar to that used for COVID-19. Leveraging the existing testing infrastructure can scale up eDNA metabarcoding and thus reduce costs. This could be implemented across Germany and the EU, providing a standardized and accurate tool for measuring soil biodiversity.

However, further research from universities and other academic bodies is required to improve soil biodiversity measuring. Efforts could include improving the accuracy of eDNA metabarcoding, developing alternative indices of soil biodiversity, identifying additional critical information on SOM and its drivers, and investigating the critical relationship between above- and belowground biodiversity. More field trials regarding soil biodiversity should also be conducted and the quantity and quality of the data in soil databases should be improved.

The Soil Value Chain. Awareness of the importance and benefits of healthy soil must be increased among all stakeholders—not just farmers, agricultural inputs companies, distributors, and consultants, but also food companies, consumers, and society as a whole. Awareness efforts can then boost corporate development and startup efforts and increase investor activity. (**See the sidebar "Investing in Soil Health."**)

Agricultural companies and distributors can be engaged in discussions at trade shows and elsewhere about soil topics and their impact on agricultural products, such as the negative effects of tilling machines. Direct outreach to distributors can help identify and promote products beneficial to soil biodiversity, such as soil inoculants. Investors could be attracted through platforms such as AngelList.

Farmers can be reached at agricultural shows and through cooperatives to discuss the benefits of soil biodiversity. Agricultural magazines can spread awareness of beneficial soil practices, while universities should include soil biodiversity in their curricula to foster research and education. Consultants can write articles and present at major agricultural events like Agritechnica, and media channels can inform society about the importance of healthy, biodiverse soil.

As a next step, investment in soil biodiversity is required, primarily by universities; state research funds and grants; agricultural companies, including startups; and farmers. Universities need to provide new scientific insights on soil biodiversity, and agricultural companies and startups can then be encouraged to transform these insights into innovative solutions for farmers.

New research should also be brought specifically to the state agricultural institutes that educate farmers on recent research on soil biodiversity and how to increase it in their fields—teaching farmers about newly developed agricultural equipment that can improve soil structure, for example. Agricultural companies should invest in R&D to convert new university research on soil biodiversity into practical products, such as new measurement techniques and equipment that minimizes soil disturbance. Farmers should be encouraged to adopt these new technologies, participate in field trials, and invest in equipment designed to improve soil biodiversity.

> Agricultural companies should invest in R&D to convert research into practical products, such as new measurement techniques and equipment that minimizes soil disturbance.

Policies and Incentives. To foster soil health, it is crucial to define policies and incentives promoting practices that improve soil biodiversity. Proper awareness and investments can incentivize farmers to adopt agricultural practices that enhance soil biodiversity. These efforts could begin by targeting specific measures, then eventually transition to providing rewards based on outcomes. Regulatory bodies and public authorities should play a key role in this endeavor, while the agricultural industry would act as an enabler for practices focusing on soil biodiversity.

Regulatory bodies and public authorities in the EU should incorporate the soil microbiome into the definition of healthy soil and establish a central open-source database for soil samples across the EU. This could be achieved by integrating soil biodiversity and eDNA metabarcoding into the EU's Good Agricultural and Ecological Practices framework (GAECs). Regulators should also promote public research projects to gain a better understanding of the drivers of soil biodiversity (such as AWHC per German soil type or the impact of beneficial practices like cover cropping) and identify harmful factors (such as the effects of climate change and tilling). After integrating soil biodiversity into agricultural measures, regulatory bodies could shift to outcome-oriented incentives, such as the EU's Common Agriculture Policy (CAP) outcome-based payments tied to soil biodiversity levels.

For the agriculture industry, including startups, developing products that enhance soil biodiversity represents a significant growth opportunity. The industry should accelerate R&D in this area, focusing on developing biologicals that enhance soil nutrients and organisms and agricultural machinery that minimizes soil disruption. Emphasis should be placed on evaluating the current product portfolio for its impact on soil biodiversity and creating complete crop production solutions that promote it.

Investing in Soil Health

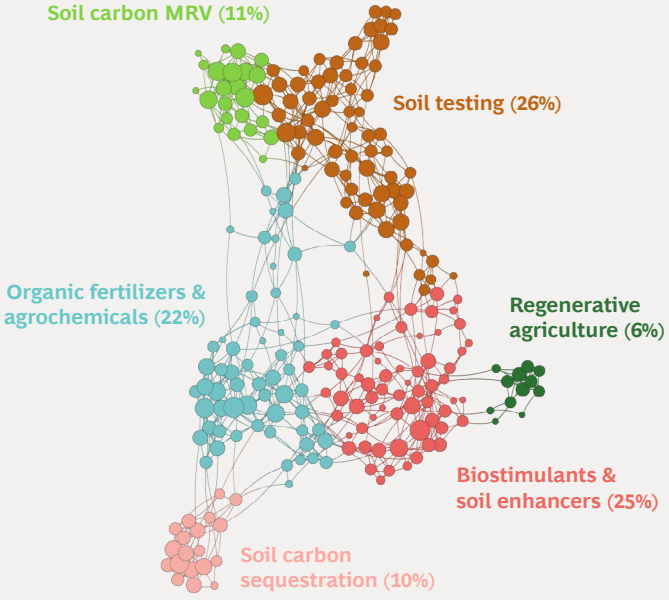
In keeping with the growing awareness of the importance of healthy soil and its economic and social benefits, technology companies, startups, and mature players in the agri-food ecosystem are finally beginning to wake up to the value to be gained in the space. Globally, more than $30 billion has been invested in soil health technologies and business models in the past ten years.

Most of the funding—between $25 billion and $30 billion, by our estimates—is going into regenerative agriculture, and most of this is linked to large food producers and processors as part of their regenerative agriculture and carbon farming programs.

Since 2019, however, venture capital investors and agricultural input players have invested $5.6 billion in a range of companies pursuing innovative technologies associated with soil health **(see the exhibit)**. Organic fertilizers and biostimulants accounted for around 60% of investment, while soil carbon sequestration is growing fastest; other areas include soil testing and MRV (measurement, reporting, and verification) methods for quantifying the amount of carbon buildup and other benefits of healthy soil, as well as agronomic advancements.

We expect investments in these areas to keep growing as awareness of the importance of soil health and biodiversity increases.

$5.6 Billion Invested Across Six Soil Health Subsectors Since 2019



	Clusters	# Companies	# Deals	Private funding[1]	CAGR (20–23)[2]
	Soil testing[3]	64	134	$0.7B	14%
	Biostimulants & soil enhancers	61	106	$1.8B	0%
	Organic fertilizers & agrochemicals	53	119	$1.8B	13%
Carbon tech	Soil carbon MRV[3]	28	44	$1.0B	31%
Carbon tech	Soil carbon sequestration	25	48	$0.3B	56%
	Regenerative farming	15	33	<$0.1B	21%

Sources: Quid (CapIQ, Crunchbase); Center for Growth & innovation Analytics; BCG analysis (analysis based on ~250 soil-health-related companies funded in the last five years).
Note: Each node represents a company; % indicates share of companies in the network; companies are sized by the degree of relevance; MRV = measurement, reporting, and verification.
[1]Investments include funding by venture capital, private equity, corporates, and institutional players.
[2]CAGR is based on investment deal count and not dollars invested.
[3]Not all soil testing & carbon MRV companies are pure play.



Conclusion

As our in-depth analysis shows, increasing soil's biodiversity has a variety of beneficial consequences—environmental, social, and economic. It can improve resilience to the increasing likelihood of droughts and floods in the face of a changing climate. It can boost the ability of soil to capture and store carbon. It can reduce the need for synthetic fertilizers and irrigation. And it can even improve the quality and nutritiousness of the food we eat.

Capturing these benefits, however, will require major efforts on several fronts. More research is needed to better understand the benefits of greater soil biodiversity and how to achieve them. Governments must provide greater support for farmers willing to learn about and employ the agricultural practices that can lead to healthier soil. And private companies and investors must develop and promote the kinds of machinery, soil inputs, and other technologies that will help farmers make their own soil more healthy.

The evidence for the real value of healthy soil is building. Now it's time for all stakeholders to put that evidence to practical use.

Appendix: Detailed Quantification of Economic Impact

DRIVERS FOR IMPACT	SOURCES
General assumptions	
Agricultural area in scope: 15.5 million ha: • Cropland: 11.4 million ha • Grassland: 4.1 million ha	• Federal Statistical Office 2020, Germany; of Germany's total of 16.3 million ha land devoted to agriculture, 0.8 million ha of peatland are excluded as out of scope.
Buildup of SOM: • Lower range: 0.8 t/ha per year • Midrange (used for quantification): 1.3 t/ha per year • Upper range: 2.9 t/ha per year	• Based on our most recent study (Kurth et al., *The Case for Regenerative Agriculture in Germany—and Beyond*, BCG, 2024) and assumed carbon capture through application of regenerative agricultural practices (with assumed adoption rates of Stage 2 practices); validated by recent results of our study in Denmark (Jameson et al., *The Potential of Regenerative Agriculture in Denmark*, BCG, 2024) • Upper and lower ranges, assuming different scenarios and stages for application of regenerative practices

Carbon

(1) Carbon capture

• Storage of carbon per ton of SOM: 0.58 tons, which equals 2.13 tons of CO_2e per ton of SOM • Buildup applied to in-scope agricultural area (15.5 million ha) and range of assumptions for annual SOM buildup (0.8, 1.3, and 2.9 t/ha per year)	According to Umweltbundesamt Germany, "Humusstatus der Böden," 2024; see dedicated section on SOM buildup

• Level of carbon price for transition path: ~ €223 per ton of CO_2e
• Other lower carbon prices (as per sensitivity analysis):
  • ~ €55/ton of CO_2e
  • ~ €157/ton of CO_2e
	• Carbon price: Predicted external climate costs based on estimated cost rates for 2030 and 2050 from the German federal environment agency (A. Matthey and B. Bünger, *Methodenkonvention 3.1 zur Ermittlung von Umweltkosten: Kostensätze*, Umwelt Bundesamt, 2020)
	• Lower alternatives considered in sensitivity analysis:
	  • Expected average voluntary agriculture-based carbon credit price in 2035, assuming euros to US dollars conversion rate of 1:1
	  • Projected mandatory carbon price in 2035 based on ETS forward price

(2) Reduction in fertilizer use (reduced carbon emissions)

• Fertilizer usage:
  • Maize (avg): 142 kg/ha N; 82 kg/ha P; 51 kg/ha K
  • Wheat (avg): 131 kg/ha N; 48.5 kg/ha P; 34 kg/ha K
  • Others (avg): 104 kg/ha N; 51.3 kg/ha P; 33.4 kg/ha K
	• Based on recommendations from Bayerische Landesanstalt für Landwirtschaft, 2024
	• Value of other crops as average of selected further crops

• CO_2 emissions/kg N fertilizer input: 5.6 tons of CO_2e/ton N	Yara, "The Carbon Footprint of Fertilizers," 2015, **https://www.yara.is/wp-content/uploads/2016/02/CO2-enska.pdf**

• Costs per ton CO_2; see "Carbon Capture" section above
• Reduction potential (at 1pp increase in SOM):
  • Maize: 6.2%
  • Wheat (avg): 4.4%
  • Others (avg): 5.3%
	Research data, adjusted with expert judgments (E. E. Oldfield, M. A. Bradford, and S. A. Wood, "Global Meta-Analysis of the Relationship Between Soil Organic Matter and Crop Yields," *SOIL*, 2019)

Nutrients

(1) Increased yields

Prices for key crops: • Maize (corn): €263.8/ton • Maize (silage): €46.0/ton • Wheat (avg. summer & winter wheat): €269.7/ton • Rye: €221.1/ton • Barley: €218.3/ton • Rape or colza seed: €551.4/ton • Potatoes: €169.9/ton • Sugar beets: €41.0/ton • Weighted average of other crops: €193/ton	• 2024 producer price based on Bayerische Landesanstalt für Landwirtschaft (maize prices based on our last regenerative agriculture study)
Base yields for key crops: • Maize: 8.4 t/ha • Maize (silage): 36.1 t/ha • Wheat (avg. summer & winter wheat): 7.6 t/ha • Rye: 5.3 t/ha • Barley: 7.1 t/ha • Rape or colza seed: 4.0 t/ha • Potatoes: 40.1 t/ha • Sugar beets: 71.2 t/ha • Weighted average of other crops: 8.1 t/ha	• 2022 yield values based on FAO
Yield increase potential (at 1pp SOM increase): • Maize (corn): 8.9% • Maize (silage): 8.9% • Wheat (avg. summer & winter wheat): 20.4% • Rye: 14.7% • Barley: 14.7% • Rape or colza seed: 14.7% • Potatoes: 14.7% • Sugar beets: 14.7% • Weighted average of other crops: 11.7%	• Oldfield, Bradford, and Wood, “Global Meta-Analysis” • Adjusted by expert assessment

Sensitivity—Total crop value: • Lower range: Estimated 2020 producer prices based on producer price index for food products • Midrange: 2024 prices • Upper range: Forecast to 2035 based on inflation rate of past five years	• Lower range: Using most conservative assumption (maize) for all crops • Midrange: Detailed yield increases per crop • Upper range: Using most optimistic assumption (wheat) for all crops
Sensitivity—Yield increase: • Lower range: ~9% • Midrange: ~15% • Upper range: ~20%	• Lower range: Using most conservative assumption (maize) for all crops • Midrange: Detailed yield increases per crop • Upper range: Using most optimistic assumption (wheat) for all crops
(2) Reduction in fertilizer use (saved costs)	
Fertilizer usage: • Maize: 142 kg/ha N; 82 kg/ha P; 51 kg/ha K • Wheat (avg): 131 kg/ha N; 48.5 kg/ha P; 34 kg/ha K • Others (avg): 104 kg/ha N; 51.3 kg/ha P; 33.4 kg/ha K	• Based on recommendations from Bayerische Landesanstalt für Landwirtschaft, 2024 • Other crops value as average of selected other crops
Fertilizer costs: • €1.06/kg N • €0.9/kg P • €0.8/kg K	• Fertilizer costs based on 2021 levels, not accounting for high price volatility in 2022–2024
Reduction potential (at 1pp SOM increase): • Maize: 6.2% • Wheat (avg): 4.4% • Others (avg): 5.3%	• Research data, adjusted with expert judgments (Oldfield, Bradford, and Wood, "Global Meta-Analysis")

Water

(1) Saved irrigation costs

Water holding capacity correlates with soil carbon capture rate and is assumed for 1pp increase in SOM
• Lower range: ~27,000 liters/ha
• Midrange: ~61,000 liters/ha
• Upper range: ~76,000 liters/ha
	• Lower range: Z. Libohova et al., "Reevaluating the Effects of Soil Organic Matter and Other Properties on Available Water-Holding Capacity Using the National Cooperative Soil Survey Characterization Database," *Journal of Soil and Water Conservation*, 2018:
	  • 0.1m depth of SOM
	  • 1 g SOM holds up to 1.5 g water
	  • 1.5 g water/g SOM = ~0.002 liters/g
	  • Conversion to liters/t assumes SOM contains 0.58% organic carbon (German Federal Environment Agency, 2022)
	• Midrange: Libohova et al., "Reevaluating the Effects of Soil Organic Matter"; scaled to 0.3m depth with slightly adjusted assumptions:
	  • 0.3m depth
	  • 1 g SOM holds up to 1.5 g water
	  • 1.5 g/g SOM = ~0.002 liters/g
	  • Conversion to liters/t assumes SOM contains 0.58% organic carbon
	• Upper range: J. Bhadha et al., "Raising Soil Organic Matter Content to Improve Water Holding Capacity," *EDIS 5* (2017)

Total irrigated cropland: 2 million ha	L. Rosa et al., "Potential for Sustainable Irrigation Expansion in a 3°C Warmer Climate," *PNAS* 117, no. 47 (2020)
Irrigation water costs: • Lower range: ~ €1.56/m³ • Midrange: ~ €2.30/m³ • Upper range: ~€3.04/m³	• Lower range: Expected average of minimal agricultural groundwater withdrawal costs and drinking water supply costs in 2035, Germany • Midrange: Average of upper and lower range • Upper range: Expected drinking water costs in 2035 based on drinking water costs in 2022 (€1.75/m³), Germany

2) Increased yield resilience	
Prices for key crops (for calculation of midrange): • Maize: €263.8/ton • Maize (silage): Not included in calculations • Wheat (avg. summer & winter wheat): €269.7/ton • Rye: €221.1/ton • Barley: €218.3/ton • Rape or colza seed: €551.4/ton • Potatoes: €169.9/ton • Sugar beets: €41.0/ton • Weighted average of other crops: €193/ton	• 2024 producer price based on Bayerische Landesanstalt für Landwirtschaft (maize prices based on our regenerative agriculture study)
Yield loss in dry year (for calculation of midrange): • Maize: 2.4 t/ha (23%) • Maize (silage): Not included in calculations • Wheat (avg. summer & winter wheat): 1.0 t/ha (13%) • Rye: 0.9 t/ha (17%) • Barley: 1.2 t/ha (17%) • Rape or colza seed: 0.3 t/ha (8%) • Potatoes: 11.4 t/ha (24%) • Sugar beets: 20.4 t/ha (24%) • Weighted average of other crops: 0.0 t/ha (<1%)	Comparison of 2017 vs. 2018 yields based on FAO data, using 2018 as exceptional year with heavy drought impact given hot and dry summer, while 2017 is considered a "normal year."
Sensitivity yield losses: • Lower range: ~ 13% • Midrange: ~14% • Upper range: ~16%	• Lower range: Based on our regenerative agriculture study, assuming selected wet years with optimal growing conditions in cycle • Midrange: Comparison of 2017 vs. 2018 yields based on FAO data, using 2018 as exceptional year with heavy drought impact given hot and dry summer, while 2017 is considered a "normal year" • Upper range: Based on our regenerative agriculture study, without assuming selected wet years with optimal growing conditions in cycle
Yield resilience (avoided yield losses through improved soil biodiversity): • Lower range: ~ 20% • Midrange: ~25% • Upper range: ~35%	• Lower range: Based on our regenerative agriculture study • Midrange: Expert judgment and farmer panel results • Upper range: Optimistic scenario based on farmer panel results; outlier applied across crops

Sources: NABU; BCG analysis.
Note: C = carbon; CO_2e = carbon dioxide equivalents; FAO = Food and Agriculture Organization of the United Nations; g = grams; K = potassium; liters/t = liters per ton; P = phosphorus; pp = percentage point; t/ha = tons per hectare.

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