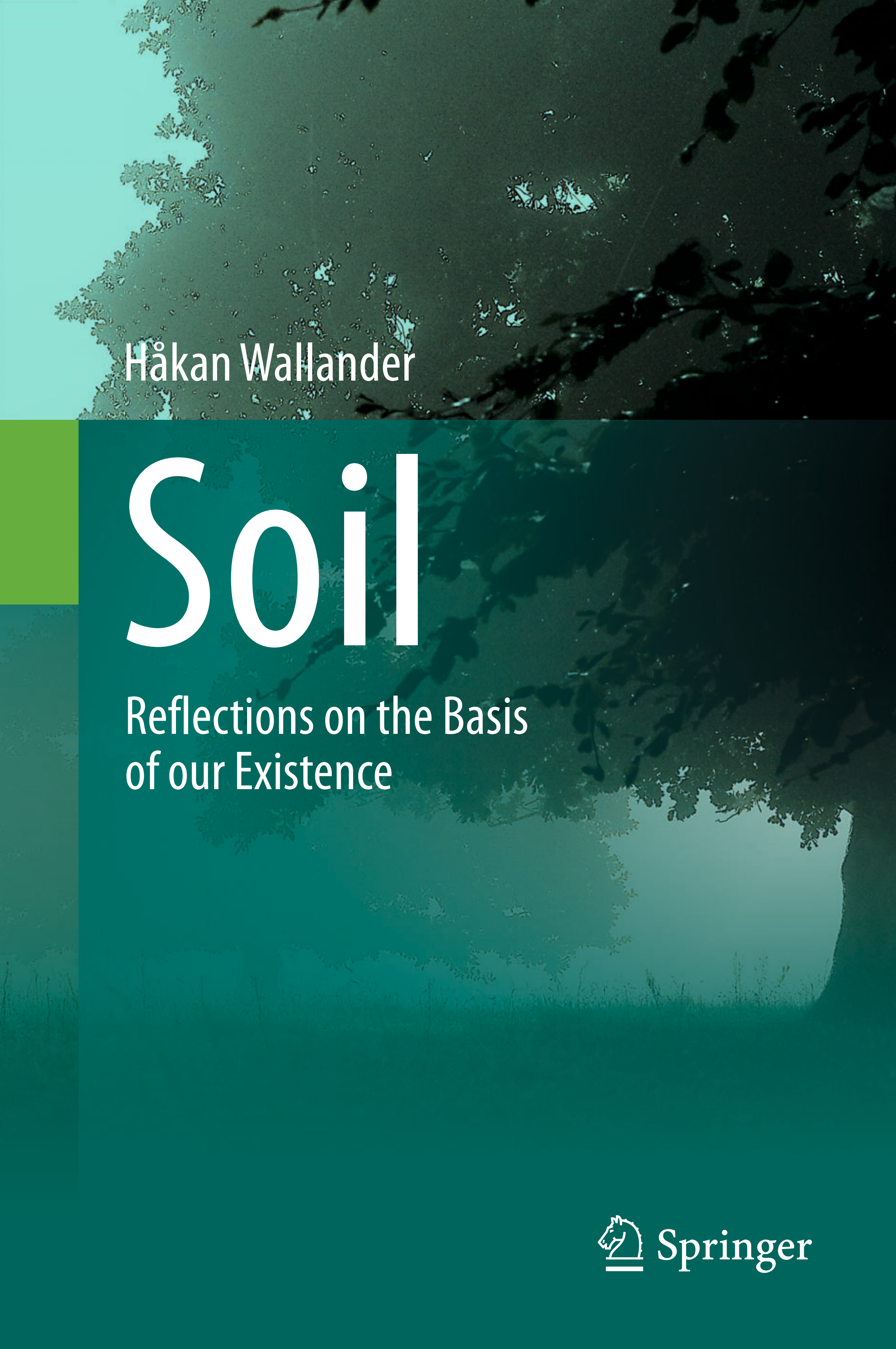

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Soil

Reflections on the Basis of our Existence

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Foreword

I have always enjoyed getting my fingers dirty, not just through gardening but also when out walking in the woods collecting samples for my research. I love rummaging among leaves and inhaling the aroma of mushrooms. Sometimes I will lift up the earth next to a large boulder to examine the tree roots. Some are yellow, others pink or black, all extending outwards in countless shapes and forms. The fungal mycelia that grow out of roots can penetrate the tiniest cavities in the soil and help the tree absorb nutrients, in return gaining access to the sugar the tree produces during photosynthesis. I have studied these fungi for 22 years, the first 7 at the Swedish University of Agricultural Sciences in Uppsala and the last 15 at Lund University.

As a scientist I have visited many exciting places: South America's rainforests, African desert, North American glaciers and the Scandinavian tundra. My travels have given me many different experiences and brought me into contact with both natural beauty and numerous interesting and knowledgeable people. Countless questions have been raised, and many are the nights I have lain awake and thought about measurements I would like to take and experiments I would like to do.

Some scientists are experts in specific soil organisms or the chemical or physical properties in the soil that relate to the life forms that grow in it. Others are more generalist in their attempts to understand how different soil components interact and how they affect critical processes like decomposition and nutrient circulation.

Some of these scientists are mentioned in this book, either in the narrative or in the references.

The book begins with a chapter on soil's importance for human life and how critical it is to preserve its properties. The chapters that follow look at how soil is formed and how soil quality affects what grows in it. The "Life in the Soil" chapter presents the life forms that inhabit the soil and the following chapter looks at how their activities enable nutrients to circulate in the soil so the wheels of life can turn. "Biological Warfare" and "A Matter of Taste" offer practical examples of how soil organisms can help us and how the soil affects the taste and quality of our food. The final chapter looks towards the future and examines how the way we manage the soil may have a profound impact on climate. This chapter may be a little harder to read, but it is a complex subject and one containing some of the toughest nuts for tomorrow's climate scientists to crack.

The pages intersperse empirical knowledge with stories from my travels and everyday life. Some of this knowledge comes from my own scientific experience, in other cases from the scientific literature or colleagues. My ambition has not been to cover all the different explanations and hypotheses for the different phenomena I describe, but rather to stimulate interest and curiosity in a subject of fundamental importance for human existence: the soil in which we grow our food and that is the basis for all land-based ecosystems. As textile artist Anna-Lisa Menander once aptly said, "You are not dirty when you have soil on your hands, you are holding a piece of eternity."

Contents

Our Indispensable Soil

As the bee collects nectar
and departs without injuring the flower
or its colour or scent,
so let a sage dwell in the community.

Buddha

Abstract This chapter describes the significance of soil for humanity. Concepts such as sustainability and nutrient balance are discussed. Most plants live in symbiosis with mycorrhizal fungi which spread their finely branched mycelium in the ground and facilitate the uptake of nutrients but the fungal hyphae also help to bind soil particles together into stable aggregates, providing a loose soil structure which is beneficial to the vegetation. Erosion, desertification and salinisation are global problems that arise when we use the land in the wrong way. My own experiences from research in Nepal and Tunisia serve here as current cases of such problems and how they can be resolved, along with historical examples of American farmers forced to abandon their farms and try their luck in California. Lastly, the chapter discusses organic farming from a sustainability perspective.

When attending a meeting at Bristol University, I was treated to a rare moment of popular science in a usually strictly academic environment. We were listening to a PowerPoint presentation full of graphs and tables describing the state of Europe's soil when a grey-bearded man wearing a woollen waistcoat approached the lectern. Squinting at the audience, he held up an apple grown organically in his garden and said it represented the Earth. He cut it in half with a knife and told us one half represented the oceans, with no soil for cultivation, and handed this piece to a colleague sitting nearby, who proceeded to take a bite. He sliced the remaining half in two and set one piece aside, saying it represented mountainous and polar terrain too cold or inhospitable for agriculture. After discarding one-eighth of the apple as representing urban areas, roads and polluted areas where crop growing was also impossible, he was left with a small segment that he carefully peeled. "This is the arable soil left for us to live on," he said, holding the thin sliver up. "We need to take care of it."

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What is Sustainable Agriculture?

All great civilisations have built their prosperity on a long tradition of farming fertile soil. Along the River Nile, rich volcanic silt washed by rainwater from the mountains of Abyssinia enabled farmers to cultivate the surrounding flood plains for thousands of years of agriculture without loss of soil fertility. The silt deposits came from once-forested slopes cleared by poor Abyssinian shepherds to create pasture for their animals. By destroying the forests, the shepherds exposed the earth to erosion and inadvertently ensured the viability of agriculture in Egypt. To this day, millions of tonnes of rich sediment accumulate on the Nile's flood plains and deltas every year.

Sustainable agriculture means ensuring that nutrients removed from the land during harvesting are replenished in equal measure. This can be through the addition of fertiliser or by flooding, as in the case of the Nile. Sustainable farming also requires that soil humus is not depleted because it is important for maintaining the soil's structure and ability to retain water. Humus decomposes at a higher rate when soil is cultivated but will increase if compost is added or plants with large underground root systems are grown. If no plant matter grows on the soil, it becomes vulnerable to erosion by wind and rain.

Inexorable soil depletion from agriculture. Soil fertility declines if the nutrients lost at harvest time are not replenished. Since 1843, scientists at Rothamsted research park in the UK have been studying how the presence or lack of nutrients affects crop yields. The bright yellow rows have had no nitrogen added to them, resulting in a yield of only 10 % of that produced in the fully fertilised rows

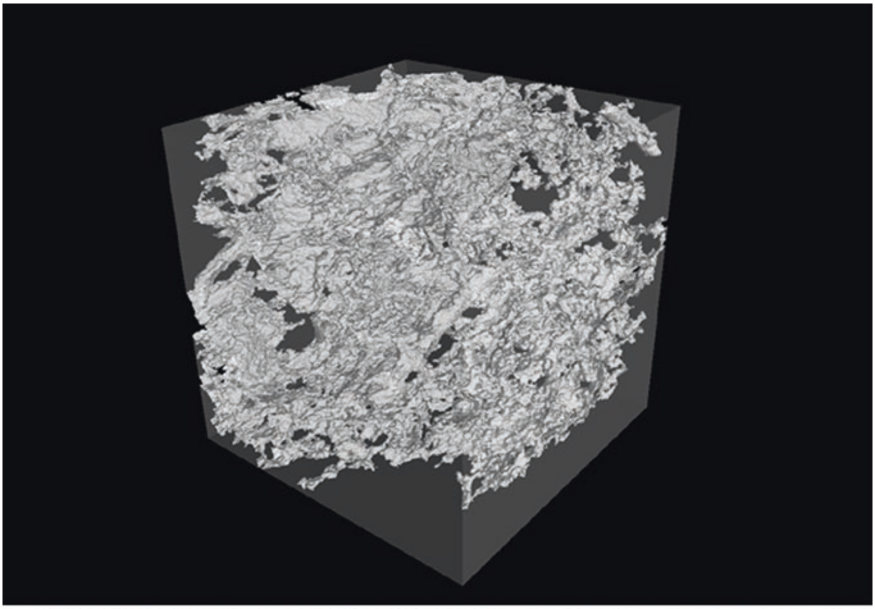
The Constituents of Soil

If you destroy the structure of the soil, with its delicate networks of pores through which air and water pass, you destroy the soil itself. The best way to preserve the soil's structure is to let plants grow in it. Plants protect the soil against raindrops, while dead plant matter in the soil supports fungi and bacteria that help keep the soil particles together and maintain a stable structure.

Soil is made up of mineral particles, organic substances, air, water and living organisms. Pick up a handful of soil and you will notice that it consists of lumps of varying sizes. These are known as aggregates and can be as small as a tenth of a millimetre across. Aggregates bond to create larger lumps that together give the soil its porosity. Without them, the soil would be dense and impermeable. Aggregates are formed by mineral particles that adhere to organic matter via slime secreted by fungi and bacteria. The excrement of earthworms is beneficial to soil because the worms' stomachs are filled with slime-creating bacteria. The aggregates are held together by thread-like fungi hyphae, which are also coated in water-repellent substances that prevent the soil from collapsing during rainfall.

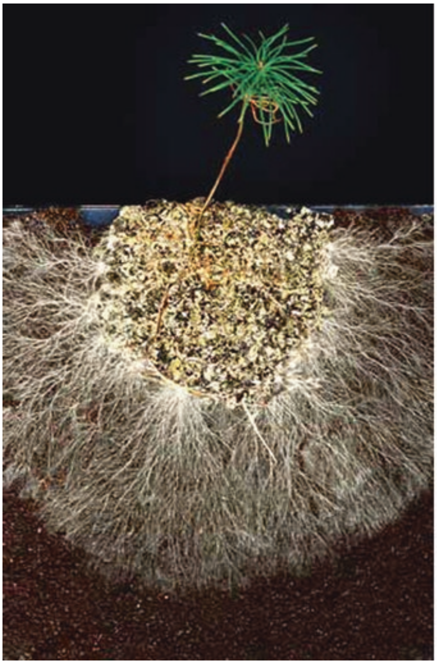
The soil's network of pores is essential to enable air to reach plant roots and oxygen-reliant organisms and for water to penetrate the earth. Digging by terrestrial animals helps porosity by creating hollows in the ground, but pores are most concentrated around plant roots, where biological activity is greatest. Roots secrete carbohydrates and amino acids on which a rich microflora of bacteria and fungi depends, in turn providing food for amoebae and other small organisms that live in the soil.

Fungi that exist in a state of symbiosis with plant roots have been my specialist area of scientific study for 20 years. They are known as mycorrhizal fungi, a word that comes from the Greek *myko* (fungus) and *rhiza* (root). Ultra-thin fungal hyphae are adept at penetrating all the nooks and crannies of the soil in their quest for nutrients. They sprout from the tiniest plant roots and extend in complicated networks that also play their part in stabilising the soil structure. I like to ask my students to analyse a handful of soil from a pine forest under the microscope so they see just how ubiquitous hyphae are: they are everywhere, surrounding every particle of soil, while roots are much harder to find. Hundreds of metres of hyphae can grow from a single root tip and it is quickly apparent that the roots' function is to nourish the fungi so they can locate food sources for the tree. In return, the fungus gains carbohydrates formed by the pine during photosynthesis. This is why this symbiosis is so successful in the plant kingdom. When the sun shines, the plant benefits from carbohydrate formation but struggles to absorb sufficient quantities of minerals like nitrogen and phosphorus from the ground. By contrast, soil-dwelling fungi have to compete fiercely for scarce carbohydrates. By tapping photosynthesising plants they gain a huge advantage when competing with other organisms in the soil.



Underground transport routes. Using computer tomography, it is possible to generate three-dimensional X-ray images of undisturbed soil (*upper image*) that reveal what soil aggregates and cavities look like. The image shows a cubic centimetre of soil from a field, with all the white areas representing cavities. More than half of the soil volume can consist of pores, but this proportion decreases when soil is compacted by heavy machinery or careless feet in a cultivation bed. Plants find it harder to grow in soil that has been compacted as the air penetrates less easily to oxygen-requiring organisms

Soil that dries out forms small lumps or variously sized aggregates. Organic matter in the lumps absorbs moisture, keeping the soil humid. The cavities between the lumps are full of air, and rainwater moves through these spaces on its way down through the soil. The soil is in constant flux, with transport channels for water and air coming and going as the weather changes



Light, air, water and nutrition. A delicate mycorrhizal fungal mycelium grows from the roots of a pine seedling. The plant is cultivated on a Plexiglas plate with a thin layer of soil to reveal how the mycelium forms the tree's contact interface with the soil. The fungus absorbs the water and nutrition the tree needs and transfers it to the roots. In exchange, the fungus gains access to carbohydrates that the pine stores in its needles with the help of sunlight. All the white areas on the image are fungal mycelium, while individual roots can be distinguished in the centre of the image. In forest soil, a single teaspoon of humus can contain several hundred metres of fungal hyphae. A tree's mycorrhizal mycelium is easy to glimpse if you lift up the moss in the forest, but you need a microscope to identify the type of fungal mycelia that grow from the roots of herbs and grasses

Boundary-spanning collaboration. "Nothing in evolution makes sense except in the light of symbiosis," says symbiosis researcher Lynn Margulis, paraphrasing the classic words of the geneticist Theodosius Dobzhansky, who said, "Nothing in biology makes sense except in the light of evolution." Symbiosis—cohabitation between organisms of different kinds—is common in nature and was a prerequisite for the explosion of biodiversity on Earth. When algae and fungi met and formed lichens, we gained a new group of organisms that, in time, spread to almost all corners of the planet. Growing on the carved handshake in the photograph are crustose lichens

◀ *Nutrient-poor sand*. Grains of sand on the beach easily blow inland on the wind. Farmers in the southern Swedish provinces of Skåne and Halland suffered major problems in the mid-sixteenth century when nutrient-poor coastal sand caked their fields. One of the reasons for this erosion was the practice of using seaweed as fertiliser, which depleted growing conditions for plants such as European beachgrass and lyme grass (*pictured*), weakening their ability to hold the sand in place. Human population growth further increased the pressure on beachside vegetation and the problems persisted until the nineteenth century, when large-scale planting of pine trees took place along the coast

Desertification in Africa

One might imagine that the ability of fungi to bind soil particles together could come in handy in areas susceptible to erosion—so long as one uses plants that attract the right sort of fungi. The Swedish International Development Cooperation Agency (Sida) liked the idea and sent me on a reconnaissance trip to Tunisia, where desertification has increased due to the felling of acacia trees. So I packed my bags with test tubes and soil collection equipment and headed for the airport.

The first African I met was a young Tunisian fellow passenger on the flight to Tunis. A student at Chalmers University of Technology in Gothenburg, he told me Sweden was clean and well ordered compared to his country, where rubbish lines the streets. But he was proud of his roots and invited me to meet his family in Tunis, promising that his grandmother's couscous was altogether superior to the precooked variety one buys in Sweden. Unfortunately, I had to decline this generous offer as I needed to travel south into the desert, but I told him about my fungi and how I hoped they could help to combat erosion. As we bade each other a warm goodbye at Tunis airport I tried to picture a young Swede inviting a stranger from North Africa home to taste his mother's pickled herring or his father's aquavit.

After clearing customs I was met by Hafedh Nasr, North Africa's leading expert on mycorrhiza, with whom I was to investigate how symbiotic fungi might combat soil erosion in the savannah forests on the edge of the Sahara. The acacias in this region are highly resistant to drought, their roots capable of reaching water forty metres beneath the surface. The trees once served as a natural buffer against desert encroachment, but most have been cut down to provide food for livestock and firewood for a rapidly increasing local population. Many were destroyed during fighting between Allied and German and Italian troops during World War II and the forests today are little more than a scattered vestige of a bygone era.

Windblown sand due to inadequate vegetation is a problem not only in the Sahara. The southern Swedish province of Skåne suffered similarly in the early twentieth century, when sand blown inland from beaches rendered arable land infertile. The pine plantations along the coast today testify to how the authorities solved the problem then.

History is littered with examples of how people have been forced to flee infertile land. In *The Grapes of Wrath* and *East of Eden*, John Steinbeck relates how farmers in America's Midwest abandoned their homesteads and relocated to California when the soil on their land was blown away during a period of severe drought in the 1930s. The Midwestern prairie is especially susceptible to wind erosion and giant dust bowls darkened the skies as far away as New York. The