Food and Agriculture Organization of the United Nations

Summary for policy makers 2020

STATE of KNOWLEDGE of SOIL BIODIVERSITY

Status, challenges and potentialities

itps INTERGOVERNMENTAL TECHNICAL PANEL ON SOILS

Convention on Biological Diversity

GLOBAL SOIL PARTNERSHIP

European Commission

GLOBAL SOIL BIODIVERSITY INITIATIVE


©FAO/Matteo Sala

STATE of KNOWLEDGE of SOIL BIODIVERSITY

Status, challenges and potentialities

Summary for policy makers

Food and Agriculture Organization of the United Nations
Rome, 2020

Required citation
FAO, ITPS, GSBI, SCBD and EC. 2020. *State of knowledge of soil biodiversity – Status, challenges and potentialities, Summary for policy makers*. Rome, FAO. https://doi.org/10.4060/cb1929en

ISBN 978-92-5-133583-3 [FAO]

Cover: ©FAO/Matteo Sala

Contents

Foreword

Our well-being and the livelihoods of human societies are highly dependent on biodiversity and the ecosystem services it provides. It is essential that we understand these links and the consequences of biodiversity loss for the various global challenges we currently face, including food insecurity and malnutrition, climate change, poverty and diseases. The Agenda 2030 for Sustainable Development sets out a transformative approach to achieve socio-economic development while conserving the environment.

There is increasing attention on the importance of biodiversity for food security and nutrition, especially above-ground biodiversity such as plants and animals. However, less attention is being paid to the biodiversity beneath our feet, soil biodiversity. Yet, the rich diversity of soil organisms drives many processes that produce food or purify soil and water.

In 2002, the Conference of the Parties (COP) to the Convention on Biological Diversity (CBD) decided at its 6th meeting to establish an International Initiative for the Conservation and Sustainable Use of Soil Biodiversity and since then, the Food and Agriculture Organization of the United Nations (FAO) has been facilitating this initiative. In 2012, FAO members established the Global Soil Partnership to promote sustainable soil management and increase attention to this hidden resource. The Status of the World's Soil Resources (FAO, 2015) concluded that the loss of soil biodiversity is considered one of the main global threats to soils in many regions of the world.

The 14th Conference of the Parties invited FAO, in collaboration with other organizations, to consider the preparation of a report on the state of knowledge on soil biodiversity covering its current status, challenges and potentialities. This report is the result of an inclusive process involving more than 300 scientists from around the world under the auspices of the FAO's Global Soil Partnership and its Intergovernmental Technical Panel on Soils, the Convention on Biological Diversity, the Global Soil Biodiversity Initiative and the European Commission. The report presents the state of knowledge on soil biodiversity, the threats to it, the solutions that soil biodiversity can provide to problems in different fields, including agriculture, environmental conservation, climate change adaptation and mitigation, nutrition, medicine and pharmaceuticals, remediation of polluted sites, and many others.

The report will make a valuable contribution to raising awareness of the importance of soil biodiversity and highlighting its role in finding solutions to today's global threats; it is a cross-cutting topic at the heart of the alignment of several international policy frameworks, including the Sustainable Development Goals (SDGs) and multilateral environment agreements. Furthermore, soil biodiversity and the ecosystem services it provides will be critical to the success of the recently declared UN Decade on Ecosystem Restoration (2021-2030) and the upcoming Post-2020 Global Biodiversity Framework.

Soil biodiversity could constitute, if an enabling environment is built, a real nature-based solution to most of the problems humanity is facing today, from the field to the global scale. Therefore efforts to conserve and protect biodiversity should include the invisible array of microorganisms that make up more than 25% of the total biodiversity of our planet.

FAO Director-General

QU Dongyu

Executive Secretary of CBD

Elizabeth Maruma Mrema

©Andy Murray

Introduction

A wealth of new scientific, technical and other types of knowledge relevant to soil biodiversity has been released since the establishment of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity in 2002, the establishment of the Global Soil Biodiversity Initiative in 2011, the Global Soil Partnership in 2012, and the publication of the Global Soil Biodiversity Atlas by the European Commission in 2016.

This new wave of research is a consequence of improvement in the methods available for the study of soil organisms by the scientific community. This research has placed soil biodiversity at the heart of international policy frameworks, including the Sustainable Development Goals (SDGs). Furthermore, soil biodiversity and ecosystem services will be pivotal for the success of the recently declared United Nations Decade on Ecosystem Restoration (2021–2030).

This Summary for Policy Makers brings the key messages from the report *State of knowledge of soil biodiversity: status, challenges and potentialities* prepared by the Food and Agriculture Organization of the United Nations (FAO), the Intergovernmental Technical Panel on Soils, the Global Soil Partnership, the Convention on Biological Diversity, the Global Soil Biodiversity Initiative, and the European Commission. The report is a result of the work of over 300 scientists and experts on soil biodiversity from all regions of the world, and it presents the best available knowledge on soil biota and their ecosystem functions and services.

Key messages

1 Soil organisms drive processes that produce food, purify soil and water, and preserve both human well-being and the health of the biosphere

What is soil biodiversity?

We define soil biodiversity as the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes. Soil biodiversity is essential for most of the ecosystem services provided by soils, which benefit soil species and its multiple interactions (biotic and abiotic) in the environment. Soil biodiversity also supports most surface life forms through the increasingly well understood links between above and belowground. For humans, the services provided by soil biodiversity have strong social, economical, health and environmental implications.

Soils are one of the main global reservoirs of biodiversity, more than 40% of living organisms in terrestrial ecosystems are associated during their life-cycle directly with soils (Decaëns *et al.*, 2006). Soil organisms can be divided into different groups: microbes, micro, meso, macro, and megafauna. They include a wide range of organisms, from unicellular and microscopic forms, to invertebrates such as nematodes, insect larvae and earthworms, arthropods and their larval stages, to mammals, reptiles, and amphibians that spend considerable parts of their lives below ground. In addition, there is a great diversity of algae and fungi, as well as a wide variety of symbiotic associations between soil microorganisms and algae, fungi, mosses, lichens, plant roots, and invertebrates.

These organisms are part of a vast food web that ensures the cycling of energy and nutrients from microscopic forms through the soil's megafauna to organisms that live on top of the soil.

For the purpose of this summary the terms soil biological diversity, and below-ground biodiversity have been used interchangeably, and they include soil microbes and soil fauna. Likewise, the terms microbial diversity, soil microbes, soil microbiome and soil microorganisms are used interchangeably specifically to describe soil microbial diversity.

Contributions of soil biodiversity

The contributions of soil organisms can be grouped into three broad categories (Figure 1). First, soil **microorganisms** (i.e., bacteria, fungi) and **microfauna** (i.e., protozoa and nematodes) transform organic and inorganic compounds into accessible forms as part of their metabolism through extraordinarily complex biochemical processes. These transformations are critical for ecosystem services such as nutrient availability for the growth of plants and other organisms, soil organic matter and nutrient cycling, and the filtration, degradation and immobilization of contaminants in water and soil.

Second, soil organisms are part of a vast food web that cycles energy and nutrients from microscopic forms through the soil's megafauna to organisms that live on top of the soil. An important part of the food web is represented by **mesofauna** such as springtails and mites, which accelerate litter decomposition and enhance nutrient cycling and availability (especially nitrogen), and predate on smaller soil organisms (Figure 1).

Finally, soil **macrofauna** and **megafauna** such as earthworms, ants, termites and some mammals act as ecosystem engineers that modify soil porosity, water and gas transport, and also bind together soil particles into stable aggregates that hold the soil in place, reducing soil erosion (Figure 1).

Organization of the soil food web

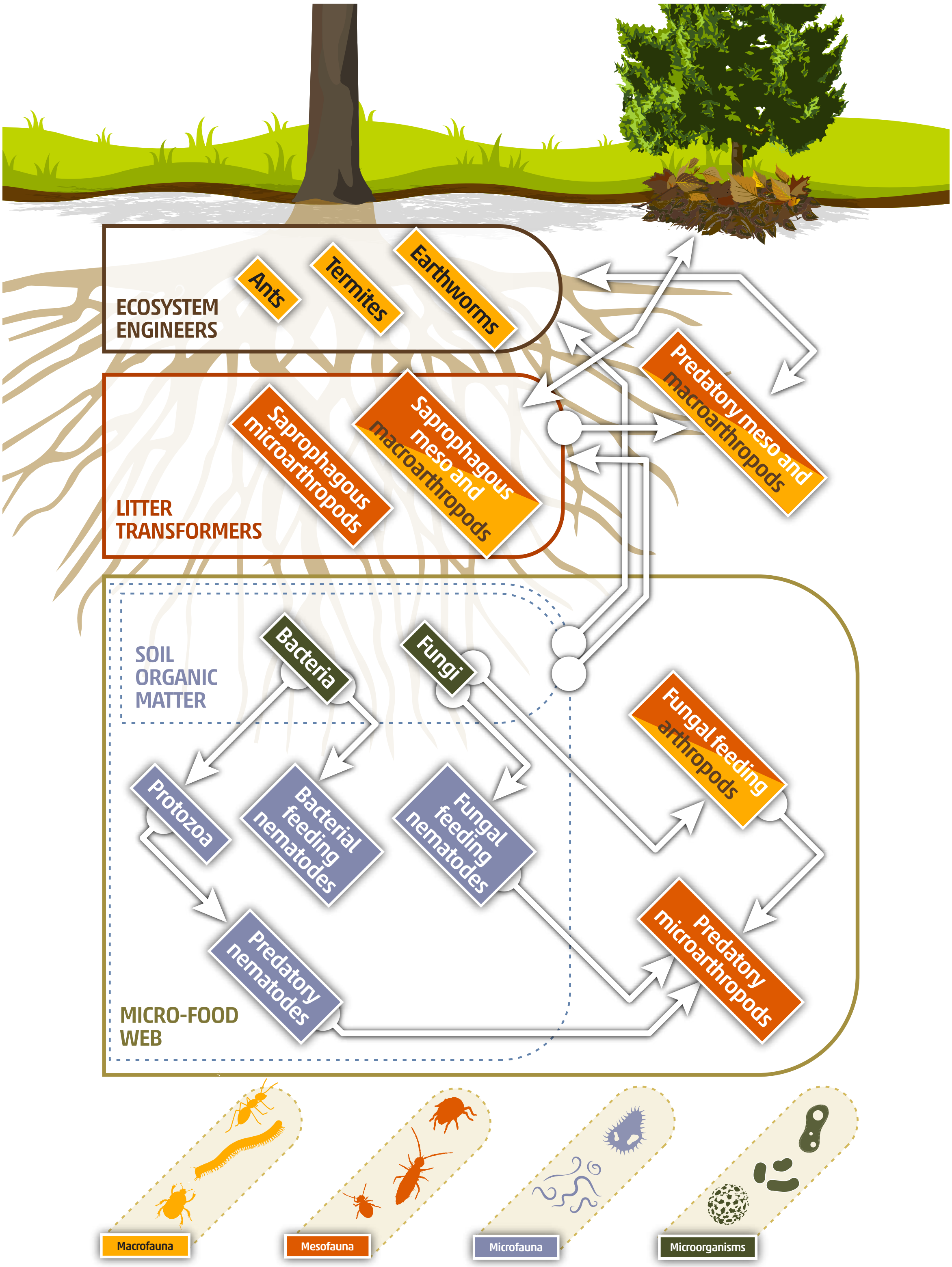


Figure 1. Simplified model with the groups of soil organisms: microorganisms, micro, meso and macrofauna grouped into three categories in the food web. First, the micro-food web (dotted lines) includes bacteria and fungi, which are at the base of the food web and decompose soil organic matter, which represents the basic resource of the soil ecosystem, and their direct predators, protozoa and nematodes. Secondly, litter transformers include microarthropods that fragment litter, creating new surfaces for microbial attack. Finally, ecosystem engineers, such as termites, earthworms and ants, modify soil structure by improving the circulation of nutrients, energy, gases and water.

Soil biodiversity and agriculture

Soil organisms both serve as a source of nutrients for plant growth and drive the transformations of nutrients that make them available to plants. The collective carbon content of all soil bacterial cells is comparable to that of all plants on earth, and their total nitrogen and phosphorous contents are far greater than that of all vegetation, making these microorganisms the primary source of indispensable nutrients for life.

Plants fix carbon from the atmosphere, but they require macro and micronutrients that are absorbed from the soil to create biomass and transfer nutrients and energy. Soil microbes and microfauna interact with abiotic factors – temperature, pH, moisture content- and drive these transformation processes.

Soil micro, meso and macrofauna play a key role in the physical breakdown of plant residues, allowing the soil microorganisms to liberate the nutrients and energy bound up in the plant material.

The role of soil organisms in agriculture has many beneficial effects beyond plant nutrition. For example, soil microbiota such as arbuscular mycorrhizal fungi and nitrogen fixing bacteria can minimise cost and dependence on synthetic nitrogen fertilizers in agriculture, and enhance soil fertility and environmental sustainability, including reducing greenhouse gas emissions from the energy-intensive manufacture of nitrogen fertilizer.

Soil biodiversity and climate change

The role of soil biodiversity in addressing global climate change cannot be understated: the soil community's activities can contribute either to the emission of greenhouse gases or to absorbing carbon into soils from the atmosphere. As part of the natural functions and ecosystem services provided by soils, a healthy soil stores more carbon than that stored in the atmosphere and vegetation combined.

Carbon is either fixed or released from soils, depending the activity of the soil organisms and driven by soil conditions. Carbon is fixed into soils through the transformation of plant and animal detritus, and also some bacteria and archaea can fix carbon by using atmospheric CO_2 as their energy source. Beyond their direct role in the carbon cycle, soil organisms are also critical for efforts to reduce overall greenhouse gas (GHG) emissions from agriculture. Globally, agricultural ecosystems contribute 10 to 12 percent of all direct anthropogenic GHG emissions each year, with an estimated 38 percent resulting from soil nitrous oxide emissions and 11 percent from methane in rice cultivation. Soil microorganisms are involved in every step of nitrogen and carbon transformations that yield these greenhouse gases, and managing the soil environment to minimise emissions is a key objective in sustainable soil management.

©Andy Murray

Soil biodiversity and human health

Soil biodiversity supports human health, both directly and indirectly, through disease regulation and food production.

Since early 1900, many drugs and vaccines have come from soil organisms, from well-known antibiotics like penicillin to bleomycin used for treating cancer and amphotericin for fungal infections. In a context of increasing illnesses due to resistant microorganisms, soil biodiversity has a huge potential to provide new drugs to combat them.

Soil biodiversity and healthy soils help to mitigate the risk of foodborne illness by boosting plant defenses against opportunistic infections. For example, the very harmful bacterium Listeria monocytogenes is found in low concentration in many agricultural soils, but its pathogenicity depends on the richness and diversity of soil microbial communities, as well as soil type, pH and other soil-related factors.

The relationship between plant roots and soil biodiversity enables plants to manufacture chemicals such as antioxidants that protect them from pests and other stressors. When we consume these plants, these antioxidants benefit us by stimulating our immune system and assist in hormone regulation.

A series of studies and evidences suggests that early exposure to a diverse collection of soil microorganisms might help prevent chronic inflammatory diseases, including allergy, asthma, autoimmune diseases, inflammatory bowel disease and depression.

Soil biodiversity and environmental protection

It is well established that preservation of soil biodiversity is critical for the maintenance and enhancement of above-ground biodiversity. The complex food webs that transfer nutrients and energy from the organic materials in the soil, through soil-dwelling organisms, to birds, mammals, reptiles and amphibians, are central to life on earth.

Soil biodiversity can attenuate threats to ecosystem services, for instance by acting as a powerful tool in bioremediation of contaminated soils. Biostimulation and bioaugmentation are environmentally sound strategies that contribute to the filtration, degradation and immobilization of target contaminants (Figure 2). Furthermore, the integral use of organisms such as microbes (bioaugmentation), plants (phytoremediation) and worms (vermiremediation) as a bioremediation strategy in hydrocarbon-contaminated soils has proven to be a viable alternative for increasing hydrocarbon removal. On the other hand, soil macrofauna, such as earthworms, termites, and ants, play an important role in improving soil structure and aggregation, which can improve resistance to soil erosion caused by wind and water.

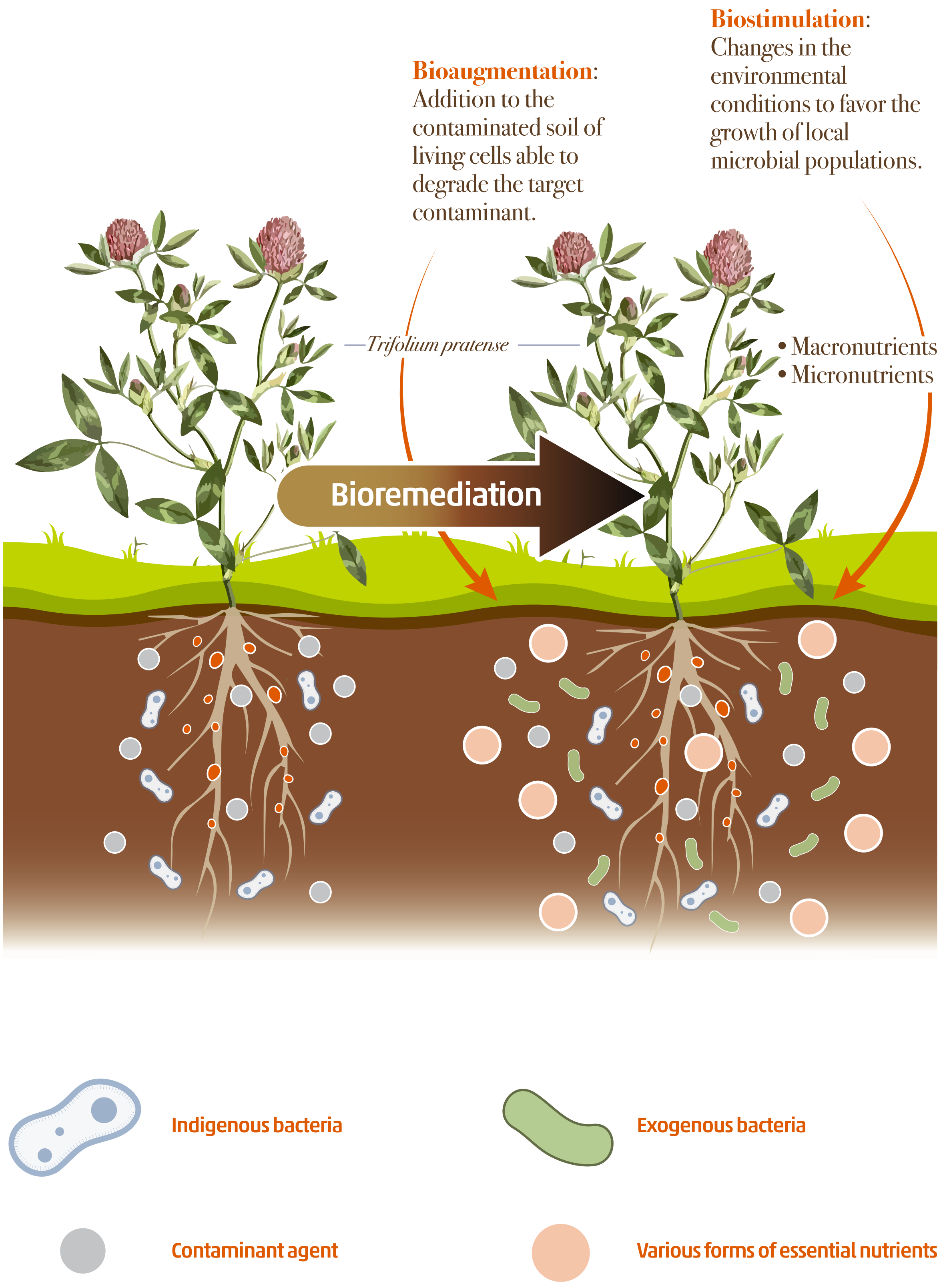


Figure 2. Soil microorganisms as a tool in the management of contaminated soils.


©FAO/Matteo Sala

2 Our current understanding of the role of soil organisms in plant growth and the transformation of pollutants has been harnessed to improve agricultural production and reclaim degraded soils

Agricultural sector

The commonly used organisms for stimulation of nutrient cycling include mycorrhizal fungi and symbiotic nitrogen-fixing bacteria (Figure 3). In Brazil and other countries in Latin America, the inoculation of selected *Bradyrhizobium* bacterial strains in soybean is an example of a major success. In 2018, soybean was cultivated in an area of about 35 million ha in Brazil. Inoculation of selected *Bradyrhizobium* strains in Brazilian soybean production totally replaced mineral nitrogen (N) fertilizers, saving billions of dollars a year. Besides its huge economic advantage, the biological fixation of nitrogen from the atmosphere by *Bradyrhizobium* is a clean biotechnology that avoids the overuse of synthetic fertilizers (Figure 4).

Soil organisms are also currently used in biocontrol measures in agriculture. The basic concept of biological control is to facilitate the natural ecosystem to counteract the potential of pests and generally to increase biodiversity and ecosystem functioning.

Worldwide, the largest commercial success of a biological control agent is without doubt *Bacillus thuringiensis* (Bt), a common bacterium isolated from soil. *Bacillus thuringiensis* is a biological control agent with insecticidal activity against a range of different insects, and different strains and marketed products increases the specificity against the target organisms (Figure 5).

Negative feedbacks between the use of soil organisms and agricultural production also occur. A significant proportion of antibiotics used in crops and livestock ends up in the soil, affecting soil biodiversity and creating antimicrobial resistance in soil-dwelling organisms.

©Andy Murray

The rhizosphere

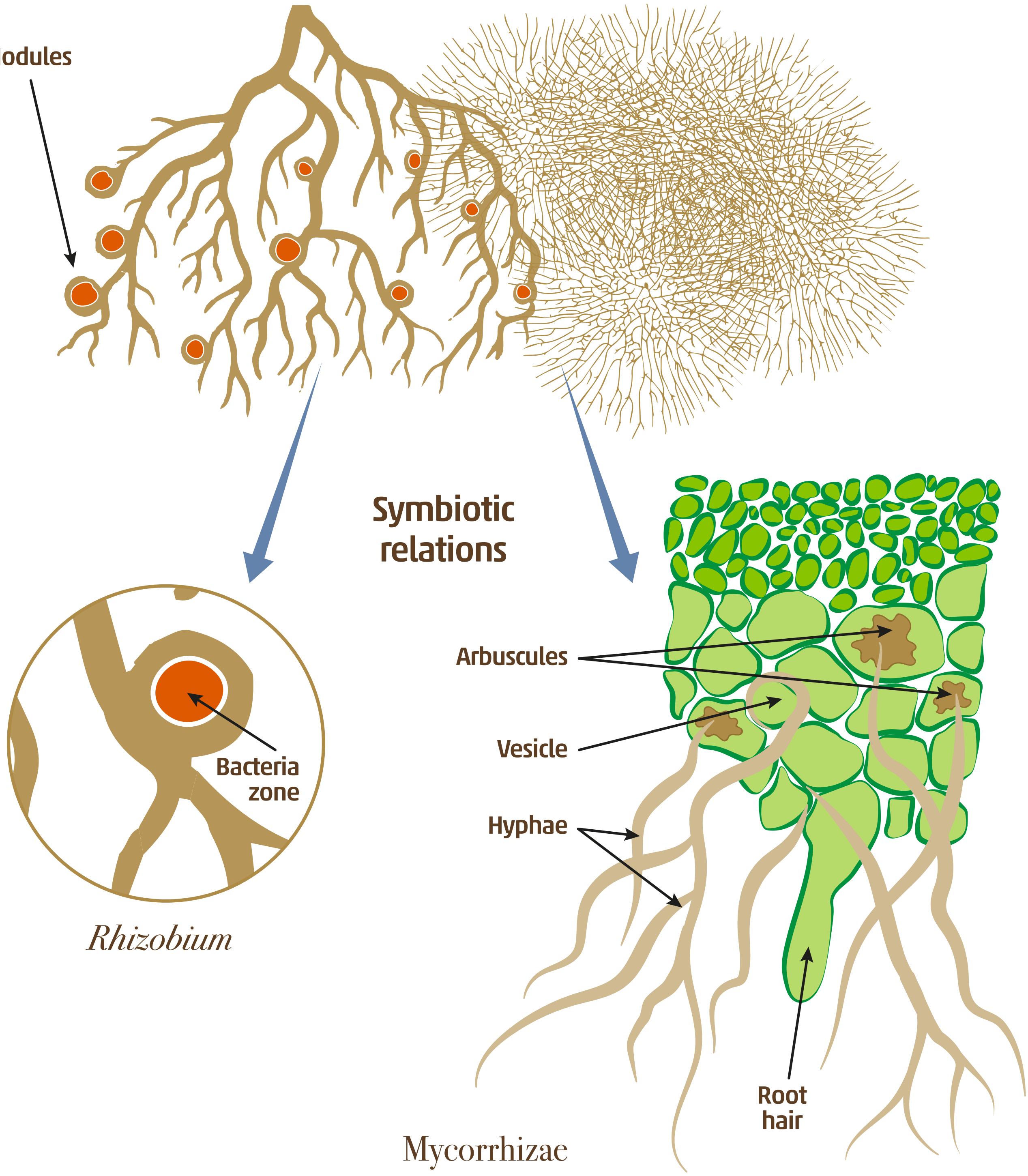


Figure 3. The rhizosphere is the narrow region of soil directly influenced by root secretions/exudates and associated microorganisms' interactions. Leguminous plants receive nitrogen –a limiting nutrient in many soils-, in the form of ammonia, thanks to rhizobium, an N_2-fixing bacteria that forms nodules in the plants' roots. In return, *Rhizobium* receives nutrients and habitat from the roots. Mycorrhizae (symbiont fungi in roots) play a key role in providing ecosystem services such as soil fertility, soil formation and maintenance, nutrient cycling and improving plant root exploration of the soil.

Clean biotechnology in agricultural production

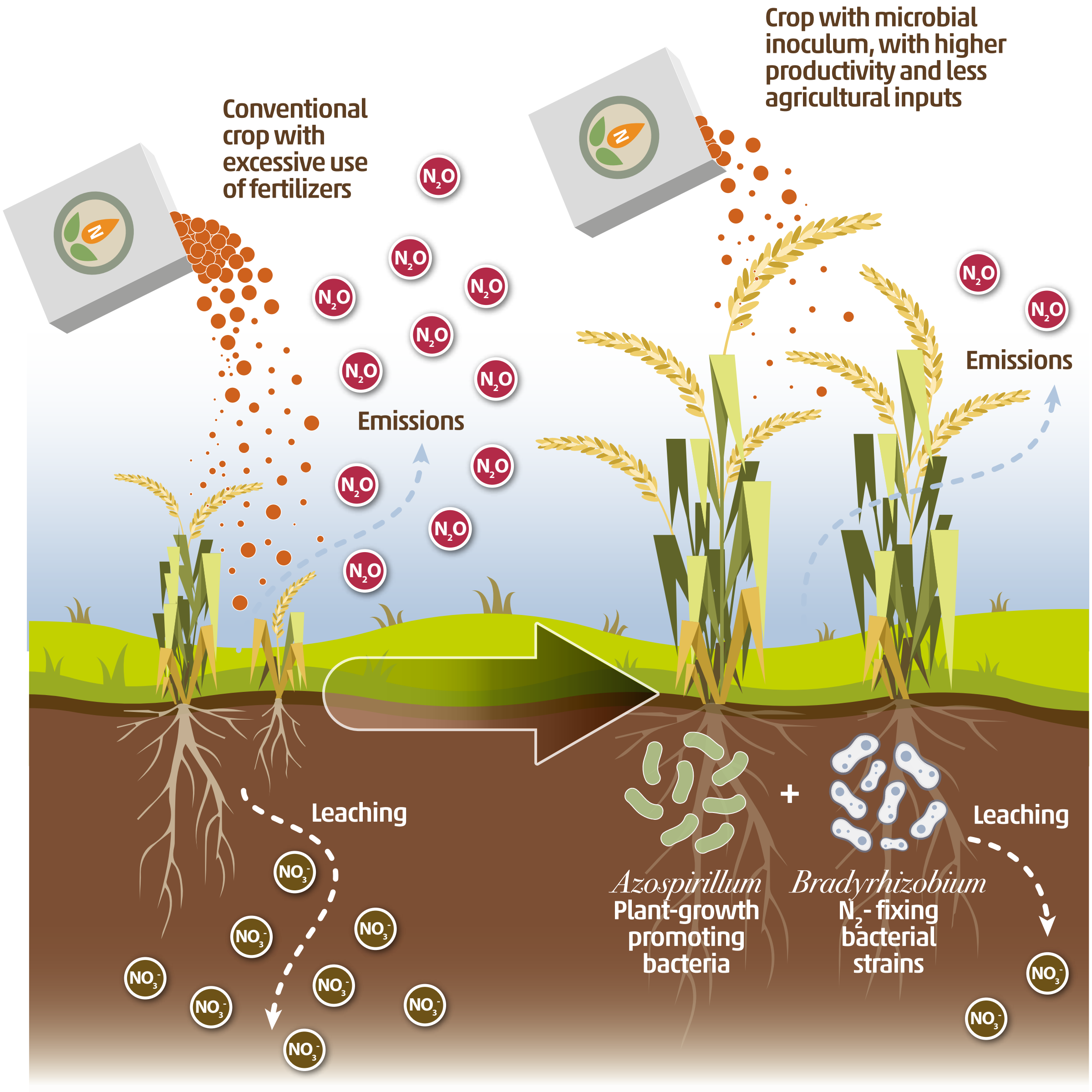


Figure 4. The co-inoculation of N_2-fixing efficient bacterial strains (*Bradyrhizobium*) with other plant-growth promoting bacteria such as *Azospirillum* in cereals, could replace part of mineral N fertilizers reducing greenhouse gas emissions such as N_2O, and diminishing leaching of reactive forms of nitrogen (NO_3^-) that contaminate underground water and coastal ecosystems; besides saving investments and capital input.

Biological control

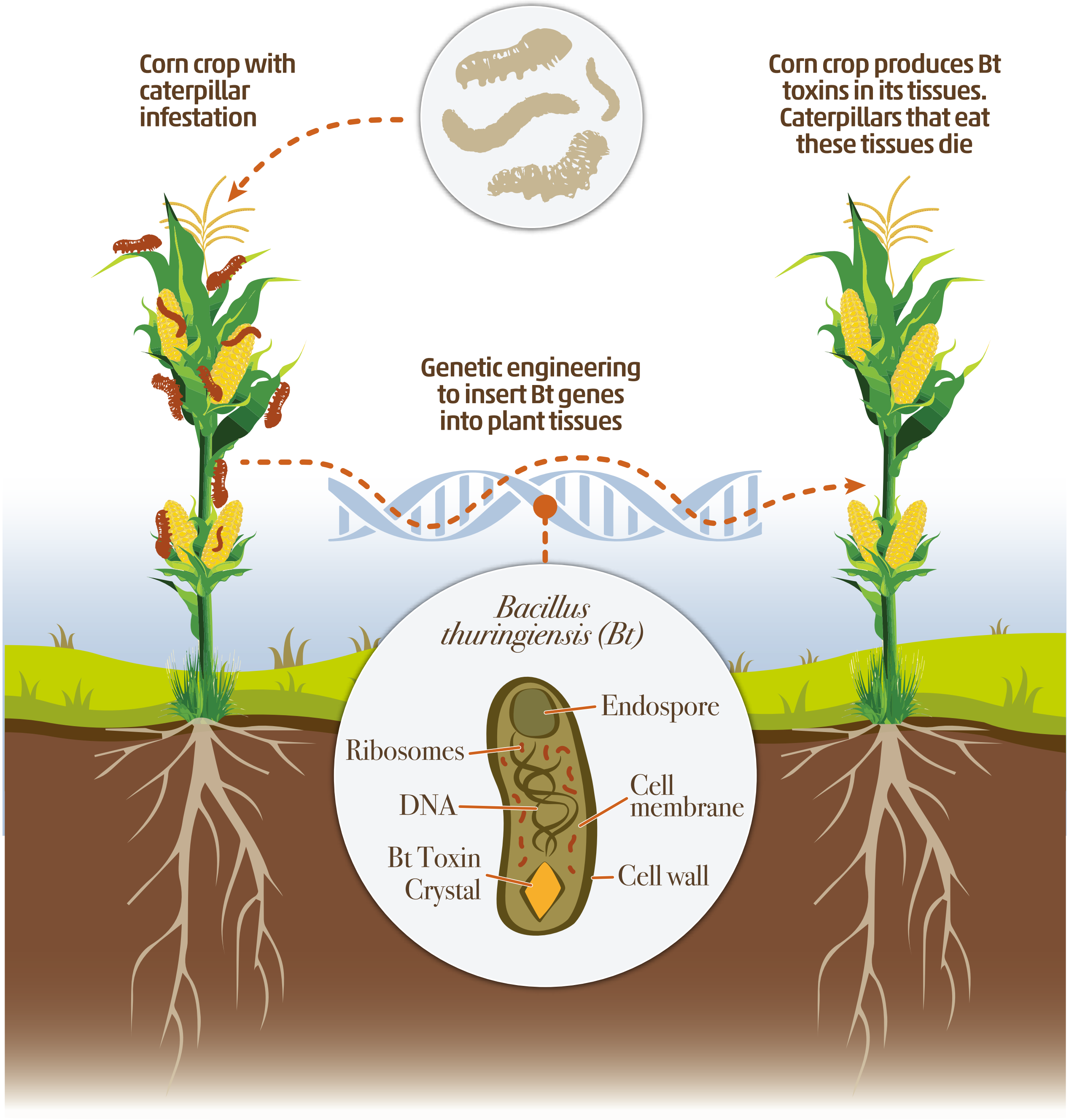


Figure 5. *Bacillus thuringiensis* (Bt), a bacterium species isolated from the soil, has been successfully used as a biological control agent against insects. Bt produces an intracellular toxin that, when ingested by an insect, is released in the insect's gut, killing it. The genes that produce the Bt toxin are inserted into agricultural crops, particularly maize, giving the plant the ability to avoid attack by certain pathogenic organisms.

Environmental remediation

Bioremediation technologies can lead to the degradation of a target contaminant to an innocuous state or to levels below concentration limits established by regulatory authorities. Soil organisms are also used directly to transform toxic compounds into benign forms through bioremediation (Figure 2). Many soil bacteria can transform different contaminants such as saturated and aromatic hydrocarbons (for example, oil, synthetic chemicals and pesticides). Soil bacteria and fungi can reduce petroleum hydrocarbons after a spill by up to 85 percent.

Challenges to use of soil organisms

Many microbial biofertilizers, biopesticides and other related products show great effects when tested under laboratory and greenhouse conditions, but fail to provide reproducible results under field conditions. One reason is the difficulty for certain organisms to survive in a highly competitive environment.

In addition to their transient and environmentally dependent effect, the high cost of biological products also restrains their adoption by farmers, and especially by smallholders with little purchasing power and poor access to credit.

In response to these limitations, some farmers with proper training attempt to reproduce native consortia of soil microorganisms to assemble biofertilizer, biocontrol and biostimulant farm inputs. To this end, farmers rely on relatively simple, rapid and affordable techniques. The use of native consortia or native microbial species –as opposed to allien species– as farm inputs may be a valid strategy for increasing biotic resistance to invasive alien pathogenic microorganisms.

3 Laboratory and analytical advances in the past decade allow us to move beyond research on individual species to study whole communities of organisms, and hence develop new approaches to address food security and environmental protection

With the advent of novel methods, researchers are now able to move beyond a focus on individual species. Scientists have started to discover how the hugely diverse soil microbiome is tied to pathogen control, plant health, increased yield, and an increased ability to overcome abiotic stress.

Especially in the last decade, method advances including molecular sequencing techniques and "big data" analytical tools have helped to identify species living in soils and their communities. Artificial intelligence has great potential in the assembly of data and the aggregation of information from multiple databases. Novel metagenomics represents a promising approach for the simultaneous study of all DNA-based information in soils, including all groups of soil organisms and functional gene information.

Agricultural industry

New molecular techniques using next generation molecular sequencing allow for improved knowledge of what organisms are in the soil, and what effects those organisms are likely to make on associated cropping systems. This knowledge provides predictive power to our understanding of how the soil systems will respond to changes in climatic factors, new cropping systems, and soil management. Other applications for these tools are the determination of which mycorrhizal fungi and nitrogen-fixing bacteria are present in the soil, and assistance to the field practitioner in assessing the efficacy of these organisms.

Soil microbiota have been found to influence the quality and longevity of harvested crops either positively (through beneficial microbial interactions) or negatively (through plant pathogens). Thus, the application of screening methods for associated biota – such as by next generation sequencing – and the subsequent necessary interventions would prove valuable in the post-harvest process. This may enhance sustainability of the full agricultural value-chain.

Food Industry

Several soil bacteria and fungi are being used traditionally in the production of soy sauce, cheese, wine and other fermented food and beverages. Lactic acid bacteria that could potentially be used to produce heavy metal absorbing probiotic products. Soils provide habitats for a variety of lactic acid bacteria belonging to *Lactobacillus*, *Lactococcus* and other genera, opening the possibility to probiotic bacteria useful in food fermentation or other processes be isolated from soils.

Ecosystem restoration

Field studies conducted at relevant scales for ecosystem restoration (i.e. hectares) have demonstrated that a whole-soil biota inoculation method representing all soil biodiversity is a powerful tool in the restoration of terrestrial ecosystems. However, the effectiveness of any soil biodiversity restoration programme depends on the appropriate integration into its landscape and the expected interactions within it. When soils have been extremely degraded, the rehabilitation of the physical and chemical properties of the substrate is necessary. Under the influence of soil-forming factors, including soil biodiversity, the development of new soils may occur (Figures 2 and 6).

Combination of soil rehabilitation strategies

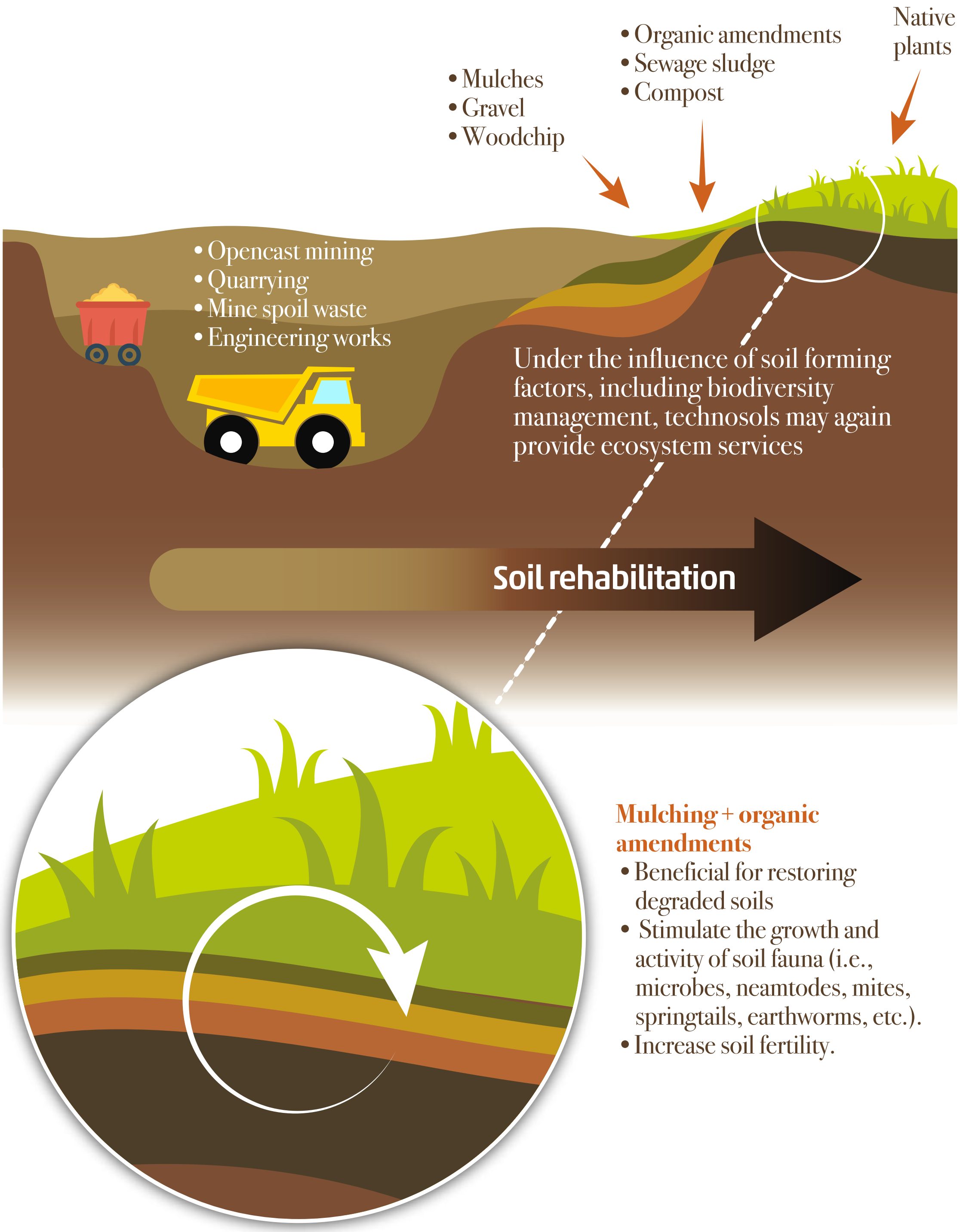


Figure 6. Mining activities have drastic negative effects on soils, especially in arid areas. An alternative to restore the biological communities of the soils is the establishment of technosols. Essential actions in the recovery of soil functionality include the addition of organic matter, which together with the action of pioneer plants, promotes the growth and activity of soil biota populations, eventually influencing the improvement of the fertility of degraded soils.

Pharmaceutical industry

Loss of soil biodiversity could limit our capacity to develop new antibiotics and tackle infectious diseases. While most biopharmaceutical research is focused on identifying unique microbes that can be developed into biotherapeutics, new technologies that make it possible to study the metagenome (or collective genome) in an environmental sample have sparked an interest in exploring how complex biological communities in soil and other indoor and outdoor environments influences human immune and nervous response via the skin, gut and lungs.

4 The essential contributions of soil organisms are threatened by soil-degrading practises. Policies that minimise soil degradation and protect soil biodiversity should be a component of biodiversity protection at all levels

The important role of soil biodiversity in ecosystem functioning and ecosystem service delivery can be threatened by human activities as well as by natural disasters, though the latter may also be influenced by human-induced changes. These include deforestation, urbanization, agricultural intensification, loss of soil organic matter/carbon, soil compaction, surface sealing, soil acidification, nutrient imbalance, pollution, salinization, sodification, desertification, wildfires, erosion and landslides (Figure 7). These co-occurring drivers of environmental change can have synergistic effects and may thus pose a particular threat to soil organisms and ecosystem functions. Deforestation and fires in particular have very negative effects on soil biodiversity, and policies designed to control and ideally reduce their occurrence will have very beneficial impacts on soil biodiversity.

©Andy Murray

Major anthropogenic threats to soil biodiversity

Deforestation
drivers and effects on soils

- Land use change
- Loss of SOM and nutrients.
- Changes in soil physical properties.
- Disruption of suitable habitat.
- Changes in pH.

Impacts on soil biodiversity

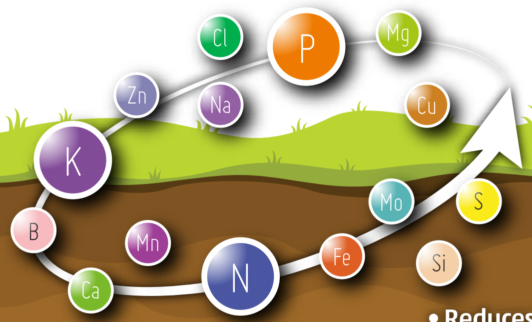
- Loss of specialist species and increase in generalist taxa.
- Decrease in predator species.
- Reduced soil and functional diversity.
- Recovery could take decades.

Agricultural intensification
drivers and effects on soils

- Greater use of external inputs (pesticides, fertilizers) and more soil disturbance.
- Greater risk of soil erosion, contamination, land degradation, compaction and salinization.
- Alteration of hydrological and biogeochemical cycles.
- Disturbance of soil structure.
- Loss of SOM.

Impacts on soil biodiversity

- Decrease in soil biodiversity.
- Smaller and less complex belowground food webs.
- Recovery of soil communities may take years or decades.
- Less efficient and functional soil food webs.
- Loss of soil carbon and nutrients through leaching.

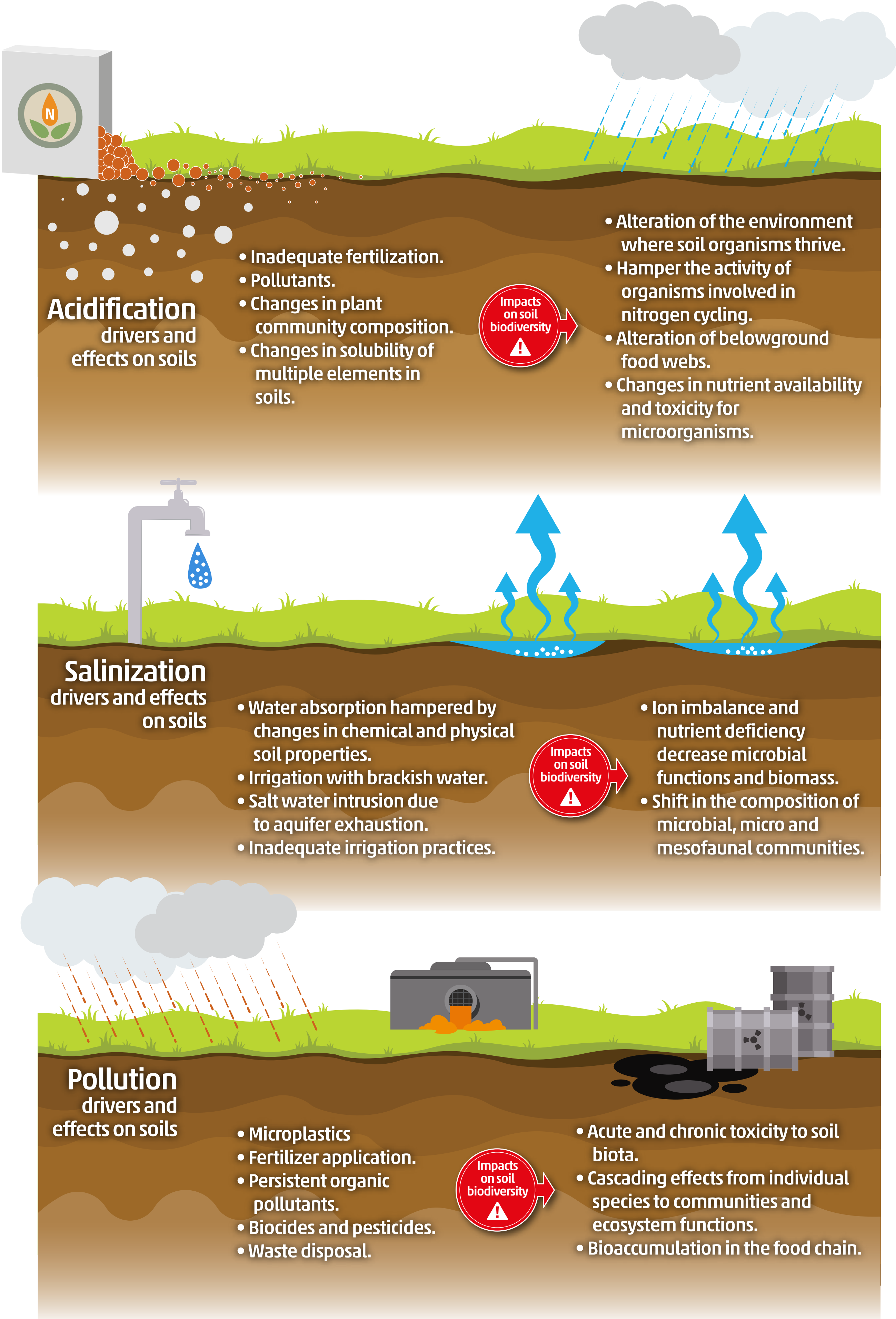


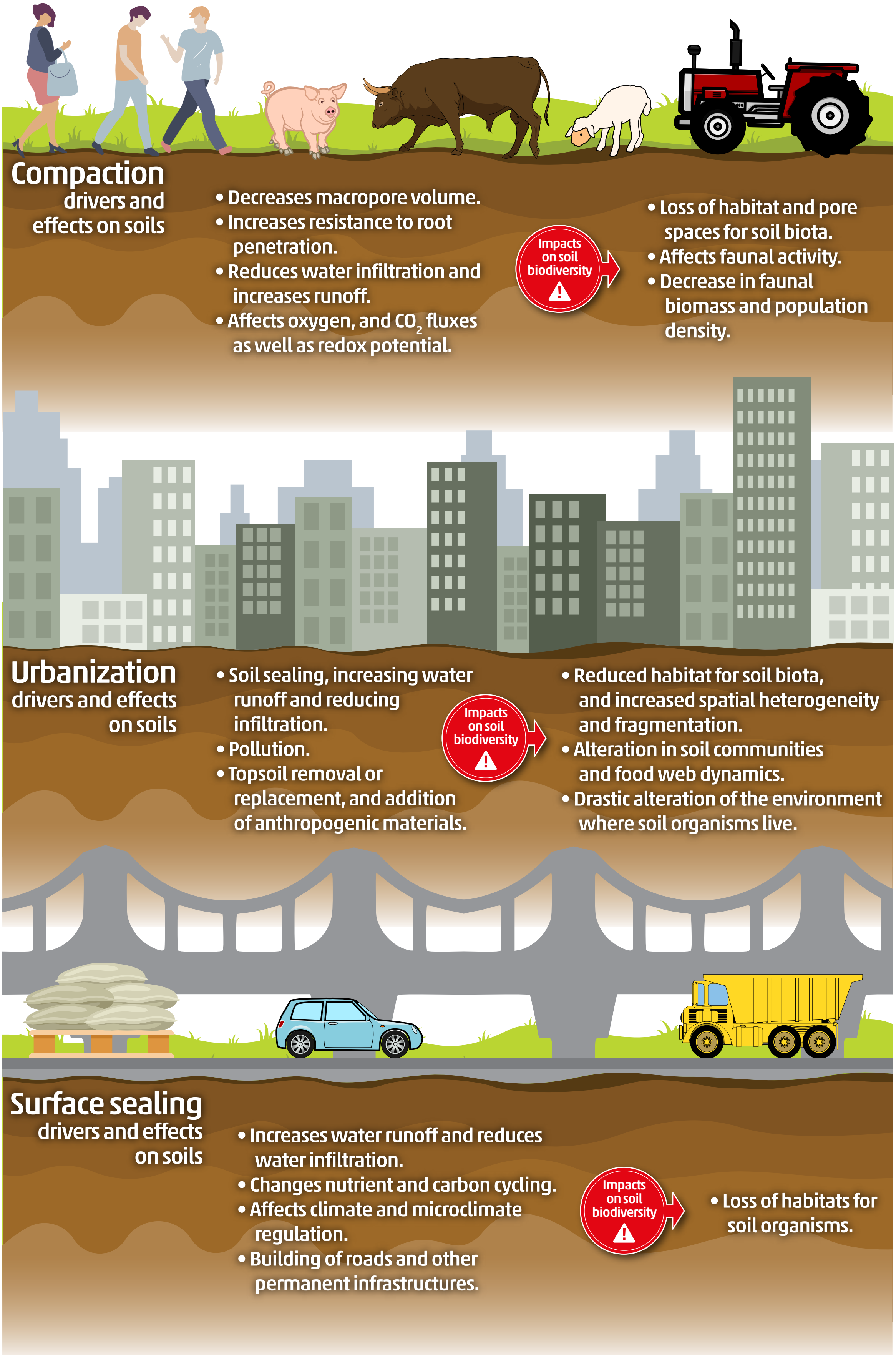
Nutrient imbalances
drivers and effects on soils

- Change in the availability of essential nutrients.
- Excessive use of mineral fertilizers.

Impacts on soil biodiversity

- Reduces the growth capacity of soil microorganisms.
- Reduces nutrient flow through the soil food web.
- Alteration of the nutritional content of primary producers and litter inputs.


N
Acidification
drivers and
effects on soils
• Inadequate fertilization.
• Pollutants.
• Changes in plant community composition.
• Changes in solubility of multiple elements in soils.
Impacts on soil biodiversity
• Alteration of the environment where soil organisms thrive.
• Hamper the activity of organisms involved in nitrogen cycling.
• Alteration of belowground food webs.
• Changes in nutrient availability and toxicity for microorganisms.
Salinization
drivers and effects
on soils
• Water absorption hampered by changes in chemical and physical soil properties.
• Irrigation with brackish water.
• Salt water intrusion due to aquifer exhaustion.
• Inadequate irrigation practices.
Impacts on soil biodiversity
• Ion imbalance and nutrient deficiency decrease microbial functions and biomass.
• Shift in the composition of microbial, micro and mesofaunal communities.
Pollution
drivers and
effects on soils
• Microplastics
• Fertilizer application.
• Persistent organic pollutants.
• Biocides and pesticides.
• Waste disposal.
Impacts on soil biodiversity
• Acute and chronic toxicity to soil biota.
• Cascading effects from individual species to communities and ecosystem functions.
• Bioaccumulation in the food chain.


Compaction
drivers and effects on soils
• Decreases macropore volume.
• Increases resistance to root penetration.
• Reduces water infiltration and increases runoff.
• Affects oxygen, and CO_2 fluxes as well as redox potential.
Impacts on soil biodiversity
• Loss of habitat and pore spaces for soil biota.
• Affects faunal activity.
• Decrease in faunal biomass and population density.
Urbanization
drivers and effects on soils
• Soil sealing, increasing water runoff and reducing infiltration.
• Pollution.
• Topsoil removal or replacement, and addition of anthropogenic materials.
Impacts on soil biodiversity
• Reduced habitat for soil biota, and increased spatial heterogeneity and fragmentation.
• Alteration in soil communities and food web dynamics.
• Drastic alteration of the environment where soil organisms live.
Surface sealing
drivers and effects on soils
• Increases water runoff and reduces water infiltration.
• Changes nutrient and carbon cycling.
• Affects climate and microclimate regulation.
• Building of roads and other permanent infrastructures.
Impacts on soil biodiversity
• Loss of habitats for soil organisms.

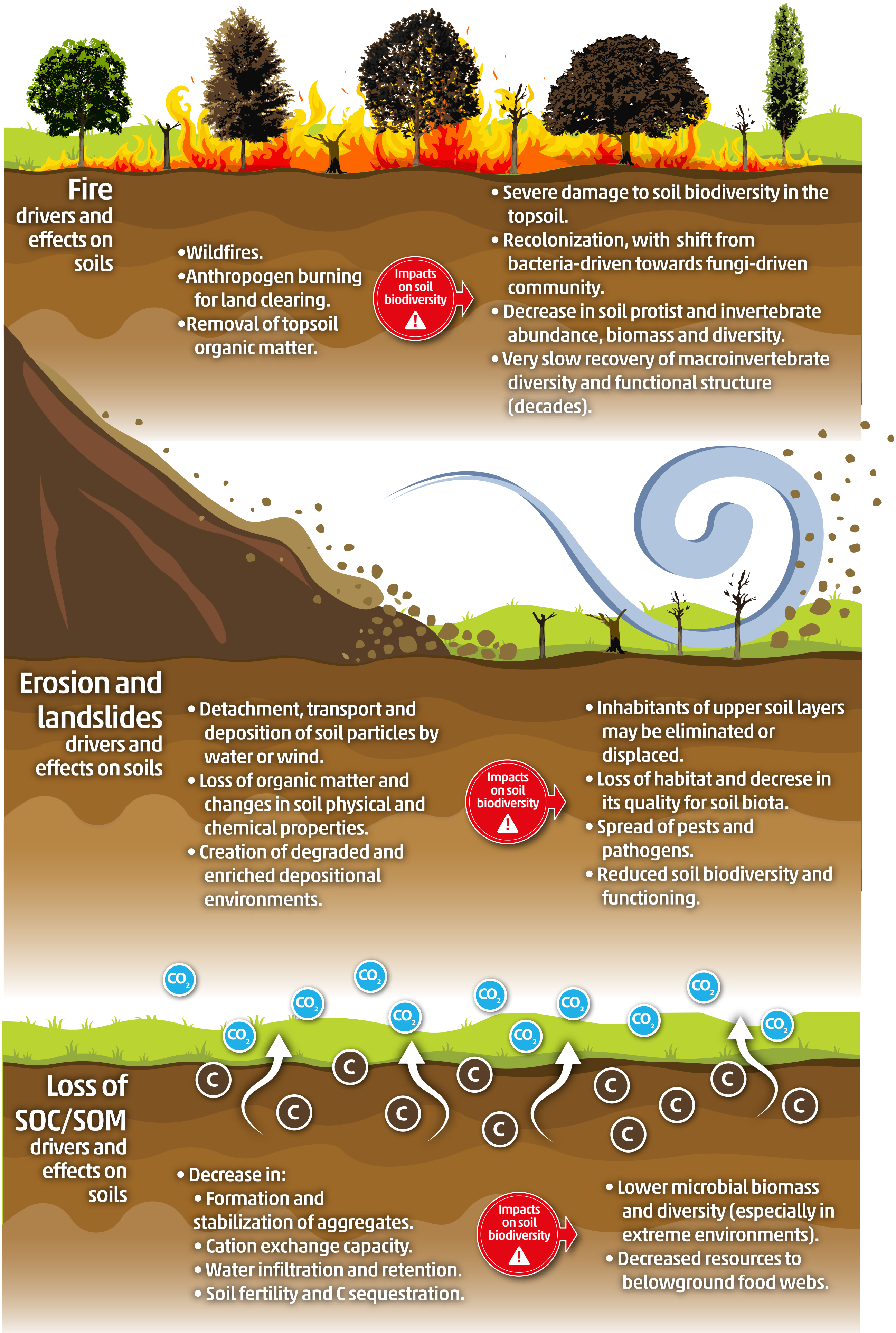


Figure 7. Major anthropogenic threats to soil biodiversity.

Invasive alien species

Most of our knowledge of invasive soil species concerns agricultural pests, of which many contribute to huge economic losses globally. Invasive alien species threaten the integrity of indigenous soil biodiversity. Non-native soil invertebrates can have dramatic negative impacts on native plants, microbial communities, and other soil animals: terrestrial invasive species can arise from any level of biological organization ranging from viruses and microbes (bacteria and fungi) to plants, invertebrates, and mammals.

Agricultural intensification

Negative impacts due to agricultural intensification have consequences for the specific functions soil animals perform, including soil structure formation and ecosystem engineering, and population regulation by predation. Human management of agricultural and other soils is known to significantly alter soil biodiversity:

Tillage: Tillage of the soil causes loss of larger soil fauna and disruption of the soil food web.

Misuse of fertilizers: Synthetic fertilization may have a negative impact on soil microbial communities and fauna. Negative impacts of synthetic N fertilization on microbial biomass, arbuscular mycorrhizal fungal (AMF) and faunal diversity have been observed.

Lime application for pH correction: Most tropical rainforest soils are naturally acidic, and often receive large quantities of lime following deforestation to neutralize pH, especially with the establishment of more intensive cropping systems. Large shifts in pH impose stress on native microorganisms, affecting their growth and reducing ecosystem resilience to disturbance.

Misuse of pesticides: Pesticides may cause resistance and bioaccumulation through the food chains. The use of pesticides can have unintended effects on soil organisms, as different organism groups react differently to various chemical substances.

Monocultures: Monocultures limit the presence of beneficial bacteria, fungi and insects, and contribute to ecosystem degradation. Large-scale monocultures also reduces soil biodiversity due to host specificity of many of the soil bacteria and fungi and larger soil fauna they attract, facilitating the spread and expression of soil-borne diseases.

Assessment of soil biodiversity

Despite recent studies -using the latest technology and artificial intelligence- on the global distribution of some soil biota orders, the current state of soil biodiversity and the distribution of many soil biota remains poorly known in many countries of the world.

Countries have assessed the status and trends of soil biodiversity in a variety of ways, including the use of scientific knowledge, the latest technologies and artificial intelligence, farmers' innovations and practices, indigenous and traditional knowledge, and mapping. Overall, there is an urgent need to continue recent efforts using the latest technologies and artificial intelligence, and to coordinate and invest in soil biodiversity assessment at the global level.

Policy development

While above-ground biodiversity is familiar to most people, and its protection is managed under national and global laws and regulations, there are few comparable activities that focus on the protection of soil biodiversity. Protecting above-ground biodiversity is not always sufficient to protect soil biodiversity. Above-ground and below-ground biodiversity are shaped by different environmental drivers, and are not necessarily linked to one another. Above and below-ground biodiversity requires tailored protection, conservation and restoration considerations because they are connected but at the same time very distinct.

To further promote the conservation and sustainable use of soil biodiversity, long-term monitoring and standardized sampling and analysis protocols must be developed. With worldwide collaboration, this should enable collation of large datasets, which are critical to amassing scientific evidence for the quantitative and functional significance of soil biodiversity.

While some countries have established indicators and monitoring tools for soil biodiversity, for the majority of countries there is a lack of knowledge, capacity and resources to implement soil health principles and adoption of best practices for soil biodiversity enhancement.

Some of the major recommendations from the report are as follows:

- Soil biodiversity needs to be reflected in National Reports and National Biodiversity Strategies and Action Plans (NBSAPs).
- Strengthen education and capacity building in the adoption of molecular tools to contribute to human, plant and soil health.
- Sustainable soil management practices should be adopted by farmers and land users to prevent and minimize soil biodiversity loss.
- Soil remediation and ecosystem restoration plans need to include soil health and soil biodiversity considerations.
- There is a need to promote the necessary shift to include biological indicators of soil health along with physical and chemical.
- There is a need to standardize sampling and analysis protocols worldwide to enable collation of large comparable datasets.
- Increase inter-sectoral and inter-institutional collaboration to explore synergies and avoid duplication or fragmentation, since soil polices can be under the responsibility of different Ministries.
- Policies and urban planning need to integrate soil biodiversity into sustainable soil management and ecosystems restoration plans to guarantee healthy soils to people by reducing urban threats to/from soil biodiversity.

The way forward

Despite the clear importance of soil biodiversity in the provision of essential ecosystem services (provision of food, fiber and fuel, filtering of water, source of pharmaceuticals, carbon and nutrient cycling, soil formation, GHG mitigation, pest and disease control, decontamination and remediation), its proper use and management is not up to scale. It is only just over a decade ago that initiatives and research networks were established to contribute to the knowhow, conservation, use, and sustainable management of soil biodiversity. These include the establishment of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity in 2002, the establishment of the Global Soil Biodiversity Initiative in 2011 and the Global Soil Partnership in 2012, and the publication of the Global Soil Biodiversity Atlas by the European Commission in 2016.

Since then, soil biodiversity has started to emerge as an alternative solution to global challenges and not only as an academic field emerged. Some countries are starting to use soil biodiversity in different areas such as agriculture, food safety, bioremediation, climate change, pest and disease control and human health. Some regions, like the European Union, have set up action plans for sustainable production, consumption, and growth to become the first climate-neutral continent in the world by 2050; soils and soil biodiversity are important components of the European Green Deal. In addition, some national institutions, research centres, networks, universities, and schools are starting to include soil biodiversity in their programmes. Some of them are also conducting research on technological innovations as well as on traditional and agroecological approaches related to soil biodiversity (e.g. research, practical application, assessment, indicators, and monitoring).

We must take advantage of this momentum to:

- Advocate for mainstreaming soil biodiversity into the sustainable development agenda, the Post-2020 biodiversity framework, the UN decade on ecosystem restoration, and all areas where soil biodiversity can contribute;
- Develop standard protocols and procedures for assessing soil biodiversity at different scales;
- Promote the establishment of soil information and monitoring systems that include soil biodiversity as a key indicator of soil health;
- Improve knowledge (including local or traditional) of the soil microbiome;
- Strengthen the knowledge on the different soil groups forming soil biodiversity (i.e., microbes, micro, meso, macro and megafauna);
- Establish a global capacity building programme for the use and management of soil biodiversity and the Global Soil Biodiversity Observatory.

A summary for policy makers with a forward looking angle is presented in Table 1.

Table 1

Summary for policy makers

Theme	Challenges/Gaps	Specific actions	*Cross-cutting actions	*Cross-cutting scopes
Understanding soil biodiversity, from cells to vertebrates	● Better understanding of microbiome (or functional groups/keystone species) networks. ● Better understanding of micro, meso and macrofauna roles in soil functions and nutrient cycling. ● More research is needed to corroborate SB data in different ecosystems and agroecosystems. ● Small and large-scale SB studies in many ecoregions of the world, especially in the southern hemisphere. ● Targeted research about the long-term impacts/risks of methods of biocontrol in the environment. ● Long-term continuous monitoring programs are needed in different ecosystems, climate types and management practices to address the temporal variability of environmental changes. ● It is necessary to develop robust and reliable biological indicators and measurement methods.	● Monitoring tools that include: new analytical approaches; advanced computing power; next-generation sequencing for the assessment of microbial SB coupled with traditional techniques; increase predictive power to changes in climatic factors, new cropping systems, and SSM; digital soil mapping tools in combination with biological information. ● Implement large-scale (watershed and landscape) SB studies. ● Include soil biodiversity in the Guidelines of Soil Survey including standard methods for measurement. ● Implement SB models based on big data generated from soil-water-plant-atmosphere information. ● Obtaining or increasing financial support to implement novel technologies -metagenomic, metabolomic, volatilomic- in developing countries. ● Establishment of a Global Soil Biodiversity Observatory. ● Support the development of community-based monitoring and information systems (CBMIS). ● Simplify methodologies and tools for soil biodiversity assessment that are directly accessible in all regions of the world. ● Mobilize targeted participatory research and development, ensuring gender equality, women's empowerment, youth, gender-responsive approaches and the participation of indigenous people and local communities. ● Increase taxonomic capacity and address taxonomic assessment needs in different regions. ● Support training in the identification and description of SB at all levels, and particularly for lesser-known taxa.	● Advocate for the implementation of SSM under the VGSSM at national level. ● Implement the use/ management and conservation of soil biodiversity as nature-based solutions. ● Promote ecosystem-based approaches that conserve, restore and avoid soil degradation and biodiversity loss. ● Develop partnerships that support multi-disciplinary approaches, foster synergies and ensure a multi-stakeholder perspective regarding SSM and SB. ● Implement the combined use of traditional knowledge, novel technologies and innovation and ensure that all relevant stakeholders have access to these tools and associated policies. ● Develop robust and reliable biological indicators, and monitoring/assessment protocols for SB. ● Raise social awareness on SB loss and recovery; threats to SB including agricultural intensification and best practices for SB assessment; and management and monitoring for all land management activities.	● Guarantee soil health for all ecosystem vitality & human well-being. ● Support agriculture for sustainability, productivity, and resource use efficiency. ● Support farmers to reduce vulnerability by diminishing production costs, increasing yields and strengthening their capacity to design and implement SSM practices. ● SB can significantly contribute to tackle environmental problems. ● The knowledge that soil is alive expands the possibilities for human-soil relationships. ● SB must be considered a natural capital asset from which ecosystem services are produced.

*This content applies to all themes addressed in table 1

SB: soil biodiversity;
N: nitrogen;
SOC: soil organic carbon;
SSM: sustainable soil management.

Theme	Challenges/Gaps	Specific actions	*Cross-cutting actions	*Cross-cutting scopes
Contributions of soil biodiversity to ecosystem services and functions	● Economic valuations of SB functions and ecosystem services provided are scarce. ● More attention must be paid to the regulation services -such as carbon storage- that rely on SB. ● It is highly necessary to develop methods to measure SB contribution to all ecosystem services affected, and at different spatial and temporal scales.	● Support projects focused on the economic valuation on SB functions and services. ● Measure SB contribution to different soil functions and services at different scales, and under different conditions. ● Develop baseline data on SB and make regular small and large-scale measurements over time. ● Better analyze the relationship between the structure of SB communities and their role in the ecosystems and agroecosystems functioning. ● Promote the adoption and feasibility of Payment for Environmental Services based on SB, with appropriate policies at various governmental levels.	● Advocate for the implementation of SSM under the VGSSM at national level. ● Implement the use/ management and conservation of soil biodiversity as nature-based solutions. ● Promote ecosystem-based approaches that conserve, restore and avoid soil degradation and biodiversity loss. ● Develop partnerships that support multi-disciplinary approaches, foster synergies and ensure a multi-stakeholder perspective regarding SSM and SB. ● Implement the combined use of traditional knowledge, novel technologies and innovation and ensure that all relevant stakeholders have access to these tools and associated policies. ● Develop robust and reliable biological indicators, and monitoring/assessment protocols for SB. ● Raise social awareness on SB loss and recovery; threats to SB including agricultural intensification and best practices for SB assessment; and management and monitoring for all land management activities.	● Guarantee soil health for all ecosystem vitality & human well-being. ● Support agriculture for sustainability, productivity, and resource use efficiency. ● Support farmers to reduce vulnerability by diminishing production costs, increasing yields and strengthening their capacity to design and implement SSM practices. ● SB can significantly contribute to tackle environmental problems. ● The knowledge that soil is alive expands the possibilities for human-soil relationships. ● SB must be considered a natural capital asset from which ecosystem services are produced.

*This content applies to all themes addressed in table 1

SB: soil biodiversity;
N: nitrogen;
SOC: soil organic carbon;
SSM: sustainable soil management.

©Andy Murray

Theme	Challenges/Gaps	Specific actions	*Cross-cutting actions	*Cross-cutting scopes
Threats to soil biodiversity	● It is crucial to envision land-use change and management as a trigger for other threats to SB. ● There are knowledge gaps in urban SB. ● Lack of knowledge of contaminant concentrations in soils and exposure thresholds for SB. ● Lack of understanding on interactive effects among multiple global change drivers on SB. ● Poor understanding of the role and impacts of threats to SB in selected ecoregions and global region. ● Inability to adequately map the importance of threats to SB at the global level.	● Consider SB and ecosystem services in land use planning. ● Foster activities to promote the practical application of SB, and integrate it into broader policy agendas for food security, ecosystem restoration, climate change adaptation and mitigation, and sustainable development. ● Promote sustainable planning management of urbanized environments and urban soil rehabilitation. ● Assessment of vulnerable species and landscapes to prioritize their protection. ● Minimise the drivers of SB loss and promote the improvement of soil health. ● Inclusion of SB into the risk assessment of agro-inputs. ● Regular assessment of soil contaminants and ecotoxicological test experiments with different target species. ● Perform detailed threat assessments on SB at various scales and/or for various taxa. ● Perform a regional and global synthesis of the threats to SB, using georeferenced and spatially relevant data. ● Promote Red-listing of endangered SB species at the national and global level.	● Advocate for the implementation of SSM under the VGSSM at national level. ● Implement the use/management and conservation of soil biodiversity as nature-based solutions. ● Promote ecosystem-based approaches that conserve, restore and avoid soil degradation and biodiversity loss. ● Develop partnerships that support multi-disciplinary approaches, foster synergies and ensure a multi-stakeholder perspective regarding SSM and SB. ● Implement the combined use of traditional knowledge, novel technologies and innovation and ensure that all relevant stakeholders have access to these tools and associated policies. ● Develop robust and reliable biological indicators, and monitoring/assessment protocols for SB. ● Raise social awareness on SB loss and recovery; threats to SB including agricultural intensification and best practices for SB assessment; and management and monitoring for all land management activities.	● Guarantee soil health for all ecosystem vitality & human well-being. ● Support agriculture for sustainability, productivity, and resource use efficiency. ● Support farmers to reduce vulnerability by diminishing production costs, increasing yields and strengthening their capacity to design and implement SSM practices. ● SB can significantly contribute to tackle environmental problems. ● The knowledge that soil is alive expands the possibilities for human-soil relationships. ● SB must be considered a natural capital asset from which ecosystem services are produced.

*This content applies to all themes addressed in table 1

SB: soil biodiversity;
N: nitrogen;
SOC: soil organic carbon;
SSM: sustainable soil management.

©Andy Murray

Theme	Challenges/Gaps	Specific actions	*Cross-cutting actions	*Cross-cutting scopes
Management of soil biodiversity	● Increase research on the field-scale performance of microbial inoculants and entomopathogenic nematodes as biological control of insect pests. ● Insufficient knowledge of the role of direct and indirect management of micro, meso and macrofauna in soil functioning and ecosystem service delivery. ● The portfolio of solutions to environmental problems is currently microbial-based; micro, meso and macrofauna are almost never included.	● Promote the prevention, suppression and control of pathogens and invasive species. ● Invest on targeted research on soil-borne diseases and promote integrated pest management. ● Privilege the development of whole community microbial inoculants over single microbial isolates. ● Implement nature-based solutions towards the micro, meso and macrofauna, not only in microbes.	● Advocate for the implementation of SSM under the VGSSM at national level. ● Implement the use/ management and conservation of soil biodiversity as nature-based solutions. ● Promote ecosystem-based approaches that conserve, restore and avoid soil degradation and biodiversity loss. ● Develop partnerships that support multi-disciplinary approaches, foster synergies and ensure a multi-stakeholder perspective regarding SSM and SB. ● Implement the combined use of traditional knowledge, novel technologies and innovation and ensure that all relevant stakeholders have access to these tools and associated policies. ● Develop robust and reliable biological indicators, and monitoring/assessment protocols for SB. ● Raise social awareness on SB loss and recovery; threats to SB including agricultural intensification and best practices for SB assessment; and management and monitoring for all land management activities.	● Guarantee soil health for all ecosystem vitality & human well-being. ● Support agriculture for sustainability, productivity, and resource use efficiency. ● Support farmers to reduce vulnerability by diminishing production costs, increasing yields and strengthening their capacity to design and implement SSM practices. ● SB can significantly contribute to tackle environmental problems. ● The knowledge that soil is alive expands the possibilities for human-soil relationships. ● SB must be considered a natural capital asset from which ecosystem services are produced.

*This content applies to all themes addressed in table 1

SB: soil biodiversity;
N: nitrogen;
SOC: soil organic carbon;
SSM: sustainable soil management.

GLOBAL SOIL PARTNERSHIP

The Global Soil Partnership (GSP) is a globally recognized mechanism established in 2012. Our mission is to position soils in the Global Agenda through collective action. Our key objectives are to promote Sustainable Soil Management (SSM) and improve soil governance to guarantee healthy and productive soils, and support the provision of essential ecosystem services towards food security and improved nutrition, climate change adaptation and mitigation, and sustainable development.

Thanks to the financial support of

Ministry of Finance of the Russian Federation

European Commission

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

ISBN 978-92-5-133583-3

9 789251 335833

CB1929EN/1/11.20