Interreg
Alpine Space

EUROPEAN UNION

Links4Soils

EUROPEAN REGIONAL DEVELOPMENT FUND

Caring for Soils
- Where Our Roots Grow

SOIL ECOSYSTEM SERVICES IN THE ALPS An introduction for decision-makers

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September 2019

Kataložni zapis o publikaciji (CIP) pripravili v Narodni in univerzitetni knjižnici v Ljubljani

COBISS.SI-ID=302174208

ISBN 978-961-6998-35-2 (pdf)

Info box

Did you know?

- Soil retains and cycles nutrients so that plants and living organisms can use them over and over again.
- About 33% of the world's soils are degraded due to erosion, acidification, compaction, salinization, pollution, loss of soil organic matter, and nutrients (FAO).
- About 50 to 70% of the world's original soil carbon stocks have been released into the atmosphere as CO_2.
- A single handful of soil may contain billions of organisms.
- Due to the thousands and even tens of thousands of years it needs to develop, soil is considered a non-renewable natural resource.

Acknowledgements

The preparation of the *"Soil Ecosystem Services in the Alps – An Introduction for Decision-makers"* was financed within the Links4Soils project, Interreg VB Alpine Space Programme. The Authors would like to thank the Joint Secretariat and Managing Authority of the Alpine Space Programme for their support and assistance in implementing the project.

We would like to express our gratitude to Jean-Baptiste Barre, Ludwig Pertl, Emanuele Pintaldi, Aleš Poljanec, Nicola Colombo, Davide Viglietti, Csilla Hudek, and Thomas Peham for their contribution and useful suggestions for improving the text.

Furthermore, we would like to thank our colleagues – the Links4Soils project partners – for all the work done. Without their contributions this booklet would not be available to readers.
We thank Mr Dean DeVos for revising the English version of the manuscript.

About the publication

Editor: Borut Vrščaj
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Logo design: GeaArt d.o.o.
Graphic design and DTP: Lirion
Production: GeaArt d.o.o.
Publisher: Agricultural Institute of Slovenia, Ljubljana, 2019

www.alpinesoils.eu

Foreword

Being the world's first international treaty aiming at the sustainable development and protection of a transnational mountain area the Alpine Convention was signed by the Alpine countries Austria, France, Germany, Italy, Switzerland, Liechtenstein, Slovenia and Monaco and by the European Union and came into effect in 1995. The Contracting Parties have committed to take appropriate measures with the objective "to reduce quantitative and qualitative soil damage, in particular by applying agricultural and forestry methods which do not harm the soil, through minimum interference with soil and land, control of erosion and the restriction of soil sealing" (Framework Convention, article 2, paragraph 2(d)).

The Soil Conservation Protocol of the Alpine Convention defines in more detail specific measures in fields such as the economical and prudent extraction of mineral resources, the conservation of soils in wetlands and moors, the designation and management of areas threatened by erosion, the limitation of inputs of harmful substances and the effects of tourism infrastructures. Other obligations concern research, education and monitoring of soil related issues.

The XV Alpine Conference in April 2019 noted that an enhanced cooperation of the Contracting Parties in the field of soil protection is required due to the increased pressure on the use of soils in the Alpine region and growing threats e.g. by climate change. Therefore, a specific Working Group on soil protection has been established with the mandate to intensify the cooperation between the Alpine states on the matter, to support the implementation of the provisions of the Soil Conservation Protocol regarding the establishment of harmonized databases and of permanent monitoring areas as well as to tackle quantitative and qualitative aspects of soil conservation and to foster exchange and awareness-raising.

The Links4Soils project and specifically this publication on soil ecosystem services in the Alps provide a sound basis for a better understanding of the benefits humans obtain from suitable management and protection of soils. Hereby the Links4Soils project contributes substantially to a proper implementation of the Soil Conservation Protocol of the Alpine Convention.

Alenka Smerkolj
Secretary General of the Alpine Convention

The European Soil Partnership

Soil is one of the vital resources that contribute to human needs. Contrary to other resources such as air or water, soil is immobile and defines countries' boundaries; however, the effects of soil functions (e.g. climate or water regulation, food production) are transboundary! If its management or protection are mainly implemented at national level through national laws and regulations, since about one or two decades, more attention is devoted to soil management and protection at the international level. The Global Soil Partnership, established by FAO in 2012, in response to the need for global action, has the mission to facilitate and promote the exchange of knowledge and technologies related to maintenance and restauration of healthy soils and proper soil functioning (http://www.fao.org/global-soil-partnership/pillars-action/en/). Based on voluntary commitment of all its members, the regional European Soil Partnership (ESP) addresses the priorities and specificities of the European region concerning sustainable soil management and soil protection http://www.fao.org/global-soil-partnership/regional-partnerships/europe/en/). Given that Europe encompasses a large array of ecological conditions, as well as many countries or regions with various local approaches and cultural specificities, sub-regional partnerships such as the Alpine Soil Partnership (AlpSP) are essential and valuable partners linking local initiatives and activities to the larger scale. The Alpine region features specific ecological, economic and social conditions and faces today specific threats, such as landslides or permafrost thawing to name just two of them. Alpine soils in all their diversity form the invisible but essential part of Alpine landscapes: the AlpSP efforts to address the soil resource in line with the ESP implementation plan (http://www.fao.org/3/a-bs972e.pdf) are a transnational contribution to achieving SDGs and ensuring the Alpine region sustainable development and future.

Elena Havlicek
Chair of the European Soil Partnership
Federal Office for the Environment, CH

The Alpine Soil Partnership

The Alpine Soil Partnership (AlpSP) is a regional initiative focused on promoting sustainable soil management and protection of the soils in the Alps, a specific region in Europe.

Therefore, the main objectives of the AlpSP are:

i) to bridge the gap between the goals of the European Soil Partnership (ESP)/Global Soils Partnership (GSP) and the local and regional levels, where soil management/protection decisions are made, and

ii) to foster the implementation of the Alpine Convention's Soil Conservation Protocol (https://www.alpconv.org/en/home/convention/protocols-declarations/).

This is necessary as soils provide essential services to humans as well as to ecosystems, while soil management is a challenging, cross-cutting topic for numerous decision-makers in several sectors, our current levels of governance, and the scientific community. Moreover, Alpine soils are intrinsically vulnerable due to their limited rate of formation, which makes them a practically non-renewable resource. The AlpSP was officially founded with the confirmation of the Memorandum of Understanding in March 2018 in Grenoble. Since then, the AlpSP has established a network based on the Links4Soils project partners and extended it to include new individual and institutional members.

The future activities of the AlpSP will focus on five key areas in the Alpine Region:

i) Sustainable soil management;
ii) Soil awareness raising, education, and didactics;
iii) Soil information and research;
iv) Regional cooperation and
v) The harmonization of data and methods.

Besides the focus on a specific region, the AlpSP also aspires to closer links to the activities of the European Soil Partnership and the FAO Mountain Partnership. Finally, the establishment of and links to other regional networks (e.g. the European Land and Soil Alliance) and institutions as well as the recruitment of new AlpSP members will continue.
For more information, see: https://alpinesoils.eu/

Thomas Peham
Office of the Regional Parliament of Tyrol

About the Links4Soils Project

Project Background

Alpine ecosystems are under increased pressure due to human influence and climate change effects. Soil is the basis of Alpine ecosystems; it is a fundamental natural resource, especially in the vulnerable Alpine Region. Through sustainable soil management and protection, we, the inhabitants of the Alps, can considerably improve the performance and resilience of key ecosystem services, preserve important natural resources and biodiversity, and thereby ensure the well-being of humans.

Soil protection in the Alps was initiated by the Soil Conservation Protocol (SCP) of the Alpine Convention (www.alpconv.org), which aims to "safeguard the multifunctional role of soil based on the concept of sustainable development and to ensure sustainable productivity of soil in its natural function, as an archive of natural and cultural history and in order to guarantee its use for agriculture and forestry, urbanism and tourism, other economic uses, transport and infrastructure, and as a source of raw materials". Unfortunately, the Soil Conservation Protocol (www.alpconv.org/en/convention/protocols) is still not adequately practised.

Project Focus

Links4Soils aims to help overcome some gaps and obstacles in soil protection and management practices in the Alps. It is focused on disseminating general soil knowledge, collecting Alpine soil data and information as well as soil management know-how, and improving the general awareness of the importance of soils and soil ecosystem services.

Some results are available at the Soil Platform (https://alpinesoils.eu). Those that might be of great interest are the best soil management practices for policy- and decision-makers, the review of the available soil data in the Alps, and soil awareness-raising information. The results can promote efficient soil protection strategies in the day-to-day work of local and regional administrations and different sectors.

Thereby, the Links4Soil project aims to contribute to better soil protection – and the implementation of the Soil Conservation Protocol of the Alpine Convention.

Borut Vrščaj
Links4Soils project leader
Agricultural Institute of Slovenia

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Soils, Soil Threats, and Soil Ecosystem Services in the Alps

Soils in the Alps

Soils in the Alps are different from other soils in other landscapes. They are highly diverse and sometimes contain riddles. As the highest mountain range in Europe, the Alps encompass all elevation zones with their specific vegetation as well as the transition from temperate to semi-arid and Mediterranean climates. As a result of these climatic differences, one can find wet peatlands as well as very dry steppe-like soils in the Alps. The wide variety of geological settings, topography, and the redistribution of soils and other materials moreover contribute to an immense diversity of soils. Given this variety of environmental conditions, including sites from the valleys up to the mountain peaks, the properties of the soils are characterized primarily by:

- A high variability of the soil-forming factors over very short spatial scales, leading to complex patterns of soil characteristics;
- Weaker soil profile differentiation with increasing altitude;
- Typical changes of some soil properties with increasing altitude, e.g. a decrease in fine grain size, pH values, and the stability of soil aggregates;
- Multi-layered soils as well as buried soils reflecting geomorphological and human activity.

Although these rules apply, we again and again find exceptional soils that stimulate soil research and lead to a new understanding of soil development over space and time in the Alps.

The general distribution of soil types in the Alps shows some typical patterns. Since the soils in the Alps are relatively young, they are dominated by the characteristics of the geological substrates, reflecting the high diversity of Alpine geological settings. Contrary to the general stone richness of many Alpine soils, the floodplains and their soils (Fluvisols) are dominated by fine grain sizes and mineral diversity, favouring highly productive soils. Slopes at moderate elevations, mostly covered by mountain forests, provide relatively deep weathered soils (Cambisols and Luvisols). Under cold and wet conditions with coniferous trees, mainly around the treeline, very acidic soils with thick organic layers can occur (Podzols). Above the treeline, soils are generally shallow and characterized by high stone content (Leptosols), whereas in the highest elevations, frost affected soils (Cryosols) are widespread. In regions with sufficient annual precipitation, peatland areas (Histosols) can be found in some places from the valleys up to high Alpine altitudes.

Generally, soils provide a large variety of ecological functions and support biodiversity above and below the earth's surface. Humans need soils and, moreover, modify them, especially by agricultural practices, which are also very diverse in the Alps. Since fertile soils are spatially very limited and mostly found at valley bottoms and other relatively flat sites, terracing also enables the cultivation of steep terrain.

As a result of the morphological conditions and specific soil characteristics, Alpine soils are highly vulnerable to soil threats such as accelerated erosion, disturbances due to mass movements and floods, the loss of soil organic matter, degradation brought by land-use change (e.g. soil sealing due to housing and infrastructure development), but also due to climate change. The need for locally adapted soil management strategies for effective planning and sustainable soil management is clear. In most Alpine regions and countries, the availability of consistent soil data is limited to agricultural land at lower elevations. Far less is known about the forest soils in the Alps, and hardly any information exists about soils above the treeline. In summary, there are huge gaps in general knowledge regarding both the specific characteristics and vulnerabilities of Alpine soils as well as soil threat mitigation practices in the Alps.

◄ **Figure 1:**
Soils in Fotsch valley; Tyrol, Austria (Photo: D. Schäfer). Alpine soils are important components of the mountainous landscape, showing specific features that help us to understand the environmental conditions.

Soil Threats in the Alps

As a result of the extreme topography and climatic conditions, the soils in the Alps are exposed to strong morphodynamic processes consisting of the erosion, transport, and accumulation of soil and loose rock by water runoff and wind, and are as well subject to debris flows, landslides, snow gliding, and avalanches. All of these natural processes are linked to climate and thus to the effects of climate change; most of seem to be accelerated in recent decades. Additionally, land-use changes such as tree-cutting and other disturbances of the Alpine ecosystems are among the main drivers of these processes. Erosion and transport processes easily destroy the thin soil cover and thus decrease or even minimize most soil functions and services. Accelerated erosion is a serious problem since new soil formation, especially at high elevations, takes thousands of years.

On the other hand, there are also soil degradation processes that take place in a more or less hidden ways, such as soil organic matter (SOM) decline. This can happen in both mineral and organic soils and is mostly triggered by unsustainable land-use management, such as draining wetlands or the overexploitation of agricultural soils, and is, moreover, intensified by global warming. In any case, the loss of SOM impairs the water holding capacity and nutrient budget of soils and also has a negative feedback effect on the carbon cycle. Thus, to a certain extent, SOM decline contributes to increasing global greenhouse gasses in the atmosphere and climate change. Due to the generally limited soil development at higher elevations in the Alps, the topsoil's function as a space for roots and thus balance the poor water and nutrient conditions of the underlying material. Nevertheless, the alteration of the organic matter is difficult to monitor and thus the scientific knowledge and level of awareness regarding SOM decline is low.

Another rather hidden soil threat is soil compaction, i.e. a reduction in soil porosity as a result of pressure on the soil surface, mostly induced by human activities involving the use of heavy machinery. Compacted soil limits root penetration and adversely affects air and water conditions, and also promotes surface runoff. Even worse are the influences of soil sealing, i.e. covering soils with impermeable materials such as asphalt and concrete. In most cases, this leads to the irreversible destruction of soils and virtually total loss of soil ecosystem services. The extension of sealed areas is generally a matter of great concern and is particularly severe in the lower parts of the main Alpine valleys with their most productive soils, and in touristic resorts. Another soil threat, largely caused by humans, is soil contamination. This refers to the presence of pollutants in soils above a certain threshold, which potentially puts the health of living beings at risk. Soil contamination is induced by the input of pollutants at specific spots (e.g. sewage or waste dumps), through diffuse deposition (e.g. traffic, industrial air emissions, housing), or in the course of agricultural production (e.g. pesticides).

The decline in biodiversity is mostly a creeping threat for soils and their ecosystem services. Soils are reservoirs of biodiversity at all relevant levels (e.g. habitat, species, and gene pool), which is reduced in terms of the number and variety of living organisms. Nevertheless, the soil organisms and their activities are fundamental prerequisites for high soil quality and thus for the provision of all soil ecosystem services. The utilization of land has a strong impact on the biodiversity of soils. Besides construction activities, also unsustainable management in agriculture and forestry (e.g. poor crop-rotation, soil compaction, extensive use of fertilizers and pesticides) negatively affects soil biodiversity.

While all of these threats play an important role in the Alps, they occur differently in terms of space and time. In order to minimize soil threats by developing suitable mitigation measures and sustainable soil management practices in different sectors, their causes and processes must be investigated, evaluated in detail, and discussed in public. This is the only way to improve and ensure sustainable soil management and protection – as well as to secure soil ecosystem services for the future inhabitants of the Alps.

▲ **Figure 2:**
Winter erosion processes due to snow-gliding and glide-snow avalanche in Valle D'Aosta, Italy (Photo: M. Freppaz)

▲ **Figure 3:**
A post-fire erosion of a forest soil; Susa valley, Italy (Photo: S. Stanchi)

▲ **Figure 4:**
Soil erosion and small soil slips caused by overgrazing in Lombardy, Italy (Photo: M. D'Amico)

Introduction to Soil Ecosystem Services

Ecosystem services – Nowadays, this is a commonly used term that attracts the attention of modern humans and promotes consideration of the benefits that the environment provides thereto. Ecosystem services are the various benefits that humans in one way or another obtain from nature or, better stated, from ecosystems. Some of the frequently mentioned and important ecosystem services are quite obvious and well recognized: food for humans and fodder for domestic animals; different kinds of biomass and raw materials such as wood for heating or furniture; and medicinal plants as well as other provisioning-type ecosystem services. The other group of ecosystem services, indeed much less recognized but somehow obvious to modern humans, is supporting and regulating ecosystem services. Plant nutrient cycling, habitats for plants and animals, primary plant growth (primary production), biodiversity, cleaning water such that it becomes potable, storing atmospheric CO_2 (a greenhouse gas) in the soil in the form of soil organic matter, and many others, are examples of supporting services that make the ecosystem function. We, humans, greatly appreciate nature, the beauties of natural and cultural landscapes, and scenic natural environments and phenomena. These services satisfy the cultural, spiritual, scientific, and recreational needs of humans. They are not fundamental in terms of survival, but largely contribute to physical and mental health and well-being. Ecosystem services are numerous, some obvious and well known, while others are hidden and not widely acknowledged.

Besides air and water, soil is the third fundamental ecosystem component that, in reality, enables life on dry land – the human environment. Being so, the question is how much and to what extent **soils contribute to the provision of various ecosystem services – soil ecosystem services** in this case.

The main purpose of this short text is to make the reader aware that soil provides an important number of ecosystem services. About 95 % of our food comes from the soil; soil filters and cleans water until it becomes potable, it cycles plant nutrients, stores carbon in soil organic matter, and preserves the remains of ancient civilizations. Soil acts as a gene pool by hosting a myriad of extremely diverse, tiny, but useful organisms. Besides the biodiversity in soil, it defines the aboveground biodiversity – diverse plant communities and interesting wildlife. Many other soil ecosystem services could be discussed here.

What is important to know is that the soil and the ecosystem services provided by soil are extremely important for life on dry land as well as human survival and well-being. This is why we need to care for soil ecosystem services and properly manage soils within diverse human activities and sectors.

There can be no sustainable development without the proper management and protection of soil.

Soil Ecosystem Services in Practice

The diversity of human activities and sectors is high. Agriculture, forestry, housing, traffic, sports, and leisure are just some of the sectors that require physical space – dedicated or actual land use. Soils provide virtually all ecosystem services in the diversity of land uses but to a different extent. Some ecosystem services are primary, and intentionally promoted in some sectors (e.g. food production on agricultural land), while others are decreased/sacrificed at the same time on behalf of the primary ones (e.g. aboveground biodiversity in terms of intensive agriculture or pure-stand forestry). Some other ecosystem services are endangered by the unsustainable practices of some sectors (e.g. water filtration and purification in the case of agriculture), while the same services remain virtually unaffected by other land uses (e.g. water purification by forest soils). Soil ecosystem services overlap in space to different extents. Two of the largest sectors, i.e. agriculture and forestry, do affect soil ecosystem services. Unsustainable conventional and industrial agriculture (intensive tillage and use of pesticides) can seriously decrease carbon sequestration, and thereby turn soils from a carbon sink to a source of CO_2. Sustainable soil practices in agriculture, e.g. conservation-tillage systems, can contribute to climate change mitigation by increasing carbon sequestration in agricultural soil and at the same time improve many other soil ecosystem services (filtering capacity, biodiversity, etc.). Sustainable forestry can contribute to better soil management by limiting soil erosion, thanks to the cautious use of heavy tree-harvesting machinery, careful selection of tree species, and returning forest monocultures (e.g. pure spruces stands) back to more natural, high-biodiversity mixed forests. Thereby, these practices would limit soil acidification, increase soil and aboveground biodiversity, and promote the 'living soil' concept.

More than half of the Earth's human population lives in urban areas. Cities are our main living ecosystem. Although not widely recognized, soils in cities provide important ecosystem services, too. In terms of urban planning, it is important to think about preserving as much soil as possible to provide a cooling effect and urban green parks and playgrounds with healthy, unpolluted, and well-functioning soils. Construction activities should be cautious and cause minimal soil compaction, pollution, and erosion. Industrial facilities should be designed better to prevent soil contamination and other adverse effects on soil and equipped with facilities preventing emissions.

It is important to decrease the pressures on soil and to preserve the largest possible area of well-functioning soils within all land uses.

Soil Ecosystem Services Logos

Soil ecosystem services (SES) are not easy to present and describe briefly. Within the Links4Soils project, we have developed logos that visually present the most important individual soil ecosystem services. The logos are used in the Links4Soils project deliverables for various purposes, e.g. to indicate which soil ecosystem services we are contributing to by means of certain planning and management activities or best soil management practices.

Description of SES Logos

Agricultural biomass production

The different horizons and the soil profile indicate the properties of fertile soil suitable for growing a variety of crops for food: the diversity and quality of food are indicated by the grain and apple.

Forest biomass production

The logo links soil properties, aboveground forest biodiversity, and forest production – timber needed for construction, various everyday products (e.g. furniture), as well as firewood for green energy.

Water retention

The drop of water lying in the middle of the soil horizons indicates the ability of soils to capture, store, and gradually release water for plants and soil biota as well as for evaporation from the soil surface.

Surface runoff regulation

The three drops percolating through the soil horizons indicate how soil largely absorbs rain, snow melt, or flooding waters and therefore reduces surface runoff through infiltration. The drops to the groundwater indicate an additional benefit: groundwater recharge.

Local climate regulation (“the cooling effect”)

The logo presents evaporation from the soil surface and indicates the transpiration of plants. Both processes are joined into evapotranspiration, which cools the surface of soils and plants and thus reduces the temperature resulting the meso- and microclimate.

Global climate regulation (“the carbon cycle”)

The logo explains different soil properties – different horizons that to a large extent define the capacity to store, exchange, and cycle carbon (C). C available in the atmosphere as CO_2, a greenhouse gas, cycles through plants to the topsoil, where it comprises soil organic matter – humus and soil organisms. When organic matter is mineralized by microorganisms, the C is returned back to the atmosphere.

Water filtration and purification

The indicated soil horizons have different capacitates to filter percolating precipitation and flood waters, to neutralize and degrade harmful substances, and to enrich the water with minerals. Water cleaned on its way through the soil profile becomes potable groundwater.

Nutrient cycle regulation

Macro and micro plant nutrients (N, P, K, Ca, Mg, and many others) are present in soil due to the microbial fixation of nitrogen, weathering and transformation of primary minerals. Without soil’s capacity to retain, exchange, and cycle nutrients in situ, soil fertility would decrease and be significantly reduced. Nutrient regulation and cycling ensures long-term soil fertility and, thereby, the vegetation cover, consisting of wild or cultivated plants.

Soil habitat and biodiversity

The different types and thicknesses of the horizons in the soil profile indicate a physical and very special place rich in soil biota. A myriad of very different organisms live in every handful of soil. The extreme diversity of life forms in soil largely exceeds the aboveground biodiversity. The so-called soil 'gene pool' is a source of useful products, e.g. medicines.

Cultural and natural archives

This amphora buried in soil represents cultural artefacts and other remains of ancient civilizations. Hidden, protected, and conserved by soil, artefacts are preserved for modern civilization. The ammonite represents the natural heritage, which in the case of soils, comprises several specific, rare, and well-expressed soil morphological features. Special formations and patterns of horizons, colours, and specific horizons need protection in a similar way as geological features.

Recreational and spiritual services

The logo unites humans and different soil properties that determine soil potentials and land uses and largely define natural and cultural landscapes. In an important way, specific soil capacities (starting with depth, water holding capacity, fertility, etc.) define land suitability and contribute to scenic landscapes and natural beauty in relation to a variety of recreational activities, sports, and spiritual benefits.

Soil Ecosystem Services

Agricultural Biomass Production

Definition: Agricultural biomass production refers to the production of plants for food, fodder, and technical fibres, as well as medicinal plants and plant biomass for (green) energy production.

Outputs: Food, fodder, technical fibre, medicinal plants, energy biomass.

Underlying soil processes: This service is based on a wide range of complex interactions of physical, chemical, and biological soil properties and processes that determine the agricultural quality of soils (in general: soil fertility). Agricultural production depends on a variety of key soil properties, e.g. soil depth, nutrient content, soil organic matter quantity and quality, water retention capacity, soil acidity (pH), soil texture and structure, mineral composition, stone content, the presence and abundance of soil biota, and several others. The agricultural biomass production SES is an essential part of the nutrient, carbon, and water cycles.

Interactions (synergies and trade-offs) with other SES: Agriculture biomass production normally depends on targeted soil management. Different agricultural practices, sustainable as well as unsustainable, have a large influence on agricultural soil quality as well as on the whole ecosystem. Agricultural practices can result in different levels of the input and output of nutrients and energy, ranging from more sustainable in terms of the preservation of soil fertility (organic farming) to less sustainable (e.g. traditional farming in developing countries, conventional farming in developed countries, and large-scale 'industrial' agriculture). Unsustainable agricultural practices also negatively affect soil fertility and biodiversity.

Agricultural biomass production strongly influences other soil ecosystem services, such as nutrient cycling, global climate regulation (the carbon cycle/carbon sequestration), water retention, decomposition and nutrient-fixing processes, and habitat provision (biodiversity). Other soil ecosystem services, such as water retention, surface runoff regulation, and cultural and natural archives, can be strongly influenced by agricultural practices.

Land-use impacts: With regard to agricultural production, we define single (and rarely several) plant species whose successful growth is promoted in order to achieve adequate yields. Sustainable agriculture promotes sustainable soil management, i.e. ensuring other environmental soil ecosystem services such as increasing soil organic carbon stocks, water filtering capacities, underground biodiversity, and, to a certain extent, aboveground biodiversity. Unsustainable agricultural practices have a large impact on other soil ecosystem services (decreased water filtration, poor water retention, a hampered nutrient cycle, decreased soil organic carbon stocks, etc.).

The impact of climate change on provision of the service: Climate change affects agricultural production through salinization, drought, heat waves, increased temperatures, excess moisture, floods, pest threats, etc. Climate change also raises awareness of changes/adaptations regarding soil management/soil tillage practices in order to secure food production for a growing population.

Demand aspects: Population growth will increase societal demand for agricultural biomass production.

Alps-specific aspects: In the Alps, agriculture has specific characteristics due to both the natural environment (topography, altitude, climate) and regional traditions. Low temperatures at higher elevations, regionally quite high or quite low precipitation, often weakly developed soils, and steep slopes induce difficult conditions for agriculture. Typical of the Alps is a high proportion of grassland in the mountain belt, which is used for meadows or mountain pasturing. Current developments show a decline in the use of marginal agricultural land in mountain areas, but also an intensification of agriculture on fields in valleys and basins. Furthermore, traditional arable mountain farming is being replaced by forage and energy crops (e.g. corn), large-scale orchards, and specifically adapted mountain vineyards.

▲ **Figure 5:**
Mountain pasture with grazers in Lombardy, Central Alps (Photo: M. D'Amico)

▲ **Figure 6:**
Typical small-scale mosaic of traditional cultural landscape in the Alps with forest, hayfields, orchards, and vineyards; Etsch valley, South Tyrol, Italy (Photo: C. Geitner).

◄ **Figure 7:**
Moderately leached Cambisol of biodiversity rich mountain pasture; Uskovnica, Slovenia (Photo: B. Vrščaj).

▲ **Figure 8:**
Deeply mixed mountain vineyard soil from till material; Eisack valley, South Tyrol, Italy (Photo: C. Geitner).

◄ **Figure 9:**
Agriculture on alpine slope and bottom of valley; Etsch Valley, South Tyrol, Italy (Photo: C. Geitner).

Agricultural Biomass Production in Brief

- **Outputs:** Food, fodder, technical fibre, medicinal plants, energy biomass.

- **Provision:** The provision of this service depends on water and nutrient availability, which is controlled by a variety of soil properties, climate, and agricultural management practices.

- **Demands:** As the world's population grows, the demand for this service will also grow.

- **Threats:** Unsustainable agricultural practices (e.g. conventional agriculture, overgrazing), soil loss (extensive sealing of the best soils, accelerated erosion) and processes (soil organic matter depletion, acidification, and salinization) as well as climate change effects hamper agricultural production.

Forest Biomass Production

Definition: The soil ecosystem service forest biomass production refers to the production of biomass from forests. Besides wood and timber, forest-derived edible products can also be considered.

Outputs: Wood, timber, wood-based biofuel, forest-derived edible wood products.

Underlying soil processes: Forests can be managed in different ways, e.g. extensive vs. intensive management. Even in the latter case, the rotation period is quite long, thus the frequency of soil disturbance due to forestry operations generally is not high, but soil protection measures are needed (e.g. harvesting in optimal soil moisture conditions). It is important to maintain a balance between logging and tree growth. The replenishment of soil nutrients is also a particular concern. Forest biomass production is based on a wide range of complex interactions of physical, chemical, and biological soil processes that support and control the nutrient and water cycles. As a consequence, they are influenced by a variety of soil properties such as soil depth, skeleton content and texture, soil structure and density, the amount and quality of organic matter and soil organisms, and pH. To what extent the soil's potential is really exploited depends on the forest species composition and the adaptability thereof.

Interactions (synergies and trade-offs) with other SES: Depending on the species composition and stand structure, forests provide a wide range of additional services related, for instance, to surface runoff regulation, water retention, local climate regulation, global climate regulation, habitat provision, and recreation.

Demand aspects: The demand for wood products, particularly as a renewable energy source, is increasing in many areas in the World. Therefore, the pressure on soil and the demand for this ecosystem service is expected to increase.

Land-use impacts: Forest biomass production is largely controlled by climate and site characteristics but can be more or less modified by forest management. Land-use changes from forest to agricultural land and vice versa can strongly impact soils and lead to remarkable trade-offs between the provision of different soil ecosystem services.

The impact of climate change on provision of the service: Due to global warming, soil with an improved plant nutrient status might be expected and forest growth and biomass production could increase. Extreme meteorological events that alter the forest composition, e.g. windstorms and droughts, could influence the soil properties. Therefore, management practices, in particular the selection of diverse tree species, have to be tailored to mitigate climate change risks.

Alps-specific aspects: Due to the specific topography and vertical extent of the Alps, forests play an important protective role in landscapes. For decades, the amount of forested area has been considerably increasing also due to socio-economic issues (e.g. traditional farming abandonment). In the past, the forest area in the Alps was lower due to more intensive harvesting, despite the steepness or lack of forestry roads, and was sometimes not economically viable. Especially in submontane and montane altitudes, the actual tree composition does not reflect the natural one, which often results in reduced biological activity in the soil and increased vulnerability of forest stands. The rising demand for renewable energy affects the specific situation of forests in the Alps as well.

▲ **Figure 10:**
Spruce forest; Pokljuka, Slovenia (Photo: S. Stanchi).

▲ **Figure 11:**
Pure spruce stands on deep, podzolized (leached) soils developed on a carbonate moraine, Pokljuka, Slovenia (Photo: B. Vrščaj).

▲ **Figure 12:**
Shallow soil developed on a highly weathered carbonate moraine rich on organic matter, Pokljuka Plateau, Slovenia (Photo: B. Vrščaj).

▲ **Figure 13:**
Podzolized Alpine forest soil under Larch (Photo: M.D'Amico).

Forest Biomass Production in Brief

- **Outputs:** Wood, timber, wood-based biofuel, forest-derived edible wood products.
- **Provision:** The provision of this SES depends on the soil water and nutrient content, which are controlled by the soil properties, climate, and forest management practices.
- **Demands:** The demand for wood products as a renewable energy source and for building materials is increasing.
- **Threats:** Unsustainable forestry practices (e.g. inappropriate tree composition or destructive harvesting), wildfires, and climate change can impair soil fertility and promote erosion.

Water Retention

Definition: The water retention soil ecosystem service refers to the ability of soils to retain, store, and gradually release water for plant uptake: upwards for evaporation from the soil surface, as well as downwards percolation to replenish groundwater.

Outputs: Water available for plants, soil biota, and evaporation.

Underlying soil processes: This water, which normally comes from rain and snow melt, and sometimes due to flooding and irrigation, infiltrates into porous soil. In the root zone it is available for plants as well as soil organisms. The soil water retention capacity depends on both the total pore volume as well as the pore size and distribution. Both are generally determined by soil depth, soil compaction, soil texture and structure, stone content, and the amount and type of soil organic matter. The structure, density, and organic matter are strongly influenced by the activity of soil organisms, in particular that of earthworms.

The water retention capacity is affected by vegetation due to its root system and the amount and quality of litter. Inversely, as water supply by precipitation is more or less infrequent, soil water storage is essential for above- and belowground organisms. To what extent this soil potential can really be exploited depends on the available soil water content and on the root systems and root depths of the plants.

Interactions (synergies and trade-offs) with other SES: The water retention ecosystem service is among the most important soil fertility parameters; therefore, it is important for biomass production, whether food, timber, or fuel. Soil water retention largely contributes to the 'cooling effect' – local climate regulation due to transpiration and evaporation, as well as the existence of soil biota that needs soil water to live.

Land-use impacts: The capacity of soils to deliver this ecosystem service is controlled by land use and soil management. In agriculture, soil cultivation strongly influences the soil water storage potential. It can decrease it (e.g. through soil compaction by heavy machinery) or enlarge it (e.g. by humus/soil organic matter enrichment). Regarding forest management, tree species composition dictates the water storage potential due to soil biological activity, tree root systems, and soil depths.

The impact of climate change on provision of the service: In the context of climate change, droughts are likely to occur more often and longer, and thus the soil water storage ecosystem service will turn out to be crucial for both the selection of crops in agriculture as well as tree species selection in forestry. The soil water holding capacity can mitigate floods and other natural disasters only to a certain extent.

Demand aspects: Due to population growth, the societal demand for this service will increase as soil water retention is crucial for agricultural, forest, and natural biomass production.

Alps-specific aspects: In the Alps, as well as in other mountainous areas, the water retention capacity is limited due to the predominance of soils in the initial stage of development, which are usually characterized by high stone and sand and low clay content. High water retention capacity soils are found on footslopes, where deeper soils are expected, or in some floodplain areas, where deep loamy and clayey soils can be found. Generally, the high precipitation in the Alps in general mitigates the problem of severe drought stress. However, low water retention capacity is problematic in some areas with a lower precipitation rate during the vegetation period (i.e. inner alpine, dry valleys).

▲ **Figure 14:**
Deep forest soil developed floodplain sediments; Lech valley, Bavaria, Germany (Photo: C. Geitner).

▲ **Figure 15:**
Deep forest soil developed from till; Inn valley, Tyrol, Austria (Photo: C. Geitner).

▲ **Figure 16:**
Organic soils (Histosols) retain a large quantity of water; Pokljuka, Slovenia (Photo: B. Vrščaj).

Water Retention in Brief

- **Outputs:** Water available for plants, soil biota, and evaporation.

- **Provision:** Soils can capture water despite gravity and store it. Thus, water is available for plants as well as soil organisms at the site. The water retention capacity of soils depends in particular on soil depth, soil pores (thus, soil texture and structure), soil organic matter content, and soil density/compaction.

- **Demands:** Water availability for plants is essential for productive agriculture and forestry; therefore the need for this service is becoming more important with the growth of the population and due to climate change.

- **Threats:** Unsustainable forest and agricultural management practices and especially soil sealing cause a significant decrease in soil available water and lead to various degradation processes and hamper other soil ecosystem services.

Surface Runoff Regulation

Definition: This soil ecosystem service refers to reducing surface runoff through the uptake of water from rain, snow melt, or flooding.

Outputs: A reduction in surface runoff and flood risk.

Underlying soil processes: Reduced surface runoff attenuates and delays peak flows and floods, also resulting in a lower amount of erosion and thus sediment load in water courses. Infiltrated water can contribute to either delayed subsurface flow or to groundwater recharge. The uptake of water by soils depends on both infiltration (at the surface) and seepage processes (within the soil). Both processes are controlled by a variety of soil properties, e.g. soil depth, density, texture, skeleton content, soil structure, the amount and quality of organic matter, biological activity and root pattern, and organic layers and rock fragments at the soil surface. Deep soils with high skeleton and low clay and silt content and a low density, in particular, effectively provide this service. Additionally, the temporally variable soil moisture determines the provision of the service. Obviously, some of these properties are closely connected with the current natural or cultivated vegetation. Mainly dense vegetation, a pronounced and deep root system, and earthworm activity promote infiltration processes.

Interactions (synergies and trade-offs) with other SES: The infiltration of water into the soil reduces erosion and positively affects all other SES, especially by preserving the organic matter of the soil. Depending on the soil properties, infiltration does not necessarily increase the water storage as it can also quickly pass through the soil, reducing the production-related services as well as the cooling effect. Furthermore, fast percolation limits the purification and filtration service. On the other hand, recreational services can benefit from dry surfaces for sports activities.

Demand aspects: The demand for this service will increase due to the continuously growing sealed areas, which create high surface runoff, and the expansion of settlement and infrastructure areas at risk of flooding. The expected higher magnitude and frequency of heavy rainfall events in the course of climate change will also raise the demand.

Land-use impacts: The capacity of soils to deliver this service is strongly influenced by the land use and land cover type (e.g. forest, hay meadow, pasture, arable field, permanent crop). Depending on particular soil management practices and the respective consequences thereof, the service provision can be increased (e.g. through ploughing, enhancing biological activity) or decreased (e.g. through compacting, sealing).

The impact of climate change on provision of the service: In the course of climate change, higher temperatures, longer dry periods, and fire are likely to promote the development of soil crusts as well as water-repellent surfaces due to dried up organic matter, both of which reduce surface runoff regulation.

Alps-specific aspects: Depending on the regional characteristics, the potentially high annual rainfall amounts and rainfall intensity, as well as runoff regimes that are influenced by snow and ice melt, can temporarily generate a water surplus. In combination with slopes, where overland flow propagates faster and can form channels, mountain torrents and (flash) floods are more likely to occur. Furthermore, the valleys are partially heavily built-up, which raises the flood risk in two respects. First, the sealed areas prevent infiltration, and second, the present infrastructure is likely to be exposed to flooding. Therefore, temporary surface runoff reduction is of particular importance in the Alps. The runoff amount considerably depends on the soil properties. For instance, the relatively high stone content of soils on Alpine slopes increases the infiltration. Also, the compaction of soil under pastures, which cover a significant area of the Alps, can put additional strain on the system and contribute to high(er) runoff. In general, the high share of forest cover in the Alps enhances this service, yet inappropriate forest management practices related to tree composition and harvesting methods can reduce it significantly by impairing the relevant soil properties (e.g. density, litter type and thickness, humus content, cracks, earthworm burrows, and other channels water uses to drain to subsoil).

▲ **Figure 17:**
Surface runoff on pasture during a thunderstorm event; Brixen valley, Tyrol, Austria (Photo: C. Geitner).

▲ **Figure 18:**
Fresh accumulation of debris because of strong surface runoff at an alpine slope above the timberline; Kauner valley, Tyrol, Austria (Photo: C. Geitner).

◄ **Figure 19:**
A very stone-rich profile in debris flow material with weakly developed topsoil, fostering infiltration processes; Inn valley, Tyrol, Austria (Photo: C. Geitner)

Surface Runoff Regulation in Brief

- **Outputs:** The reduction of surface runoff and flood risk.

- **Provision:** The uptake of water by soils reduces the risk of flooding and erosion. Furthermore, it enables groundwater recharge. The provision of this service depends on the ability of the soil to let water in (infiltration) and pass through (seepage), both of which are processes that are controlled by a variety of soil properties and land-use types.

- **Demands:** Climate change is likely to produce extreme weather events more often. Furthermore, sealed areas are currently growing and thus the demand for natural retention is increasing.

- **Threats:** Urban and touristic developments result in sealing and unsustainable forest and agricultural management practices may lead to compaction and erosion, and thus to reduced surface runoff regulation.

Local Climate Regulation
("the Cooling Effect")

Definition: This soil ecosystem service refers to the air cooling effect of soil-vegetation complexes due to transpiration and evaporation.

Outputs: The regulation of air temperature and humidity- heat/microclimate control.

Underlying soil processes: The conversion of water from the liquid to the gas phase requires energy and thus reduces air temperature. The potential local climate regulation depends on both evaporation from the soil surface and transpiration by plants. The higher the evapotranspiration, the more energy is used and the more the temperature is lowered. In areas with dense vegetation cover, transpiration is more important than evaporation. With respect to soils, the water storage capacity controls both evaporation and transpiration, and is regulated on its part by pore volume and pore size distribution. These pore characteristics are generally controlled by soil depths, stone content, the grain sizes of fine earth, soil structure, density, and the amount and type of organic matter. Although soils constitute the water reservoir enabling and limiting these processes, evapotranspiration is a part of the water cycle and determined by the whole ecosystem.

Interactions (synergies and trade-offs) with other SES: There are distinct synergistic effects between local climate regulation and the soil ecosystem services of water retention as well as biomass production in agriculture and forestry.

Demand aspects: In the course of climate change, the cooling effect of soil will turn out to be more crucial for society, i.e. human health, and of course also for other organisms and their habitats.

Land-use impacts: The potential of soils to deliver this service is closely linked to the water storage capacity and can thus be modified by land use and soil management. Within agricultural production, practices such as conservation tillage, crop rotation and cover crops, use of organic fertilizers, etc., largely determine the soil water storage capacity. In forest production, mainly the selection of tree species is relevant as it controls biological soil activity and root systems and depths.

The impact of climate change on provision of the service: Higher temperatures in the course of climate change will generally increase evapotranspiration if water is available. Nevertheless, a change in precipitation patterns might reduce the amount of water stored in soils. In addition, soil crusts as well as water-repellent surfaces due to dried up organic matter can decrease infiltration. Therefore, changes in soil temperature and moisture regimes can damage vegetation and thus lower transpiration.

Alps-specific aspects: The small-scale and vertical structure of the Alps entails a diversity of local climates. Due to the high diversity of soil-vegetation systems, local climate regulation can be very variable, too. The transpiration capacity depends on – in addition to the availability of water (precipitation and the water storage capacity of soils) – the ability of trees to gain access to soil water. The uptake of stored soil water can be limited by the shallow root systems of some species, e.g. spruce, which is widespread in the Alps due to economic reasons.

The demand for cooling is the highest in Alpine valleys, as most settlements are located there and air temperatures are relatively high. As most valley soils can provide a great deal of water for transpiration, it is important to cultivate forests and agricultural land with species with high transpiration capacities.

▲ **Figure 20:**
Water at the slopes, within the forest and in the air. The Alps are water-rich landscape; Ziller valley, Tyrol, Austria (Photo: C. Geitner).

▲ **Figure 21:**
Local climate regulation (Photo: M. D'Amico).

Local Climate Regulation ("Cooling Effect") in Brief

- **Outputs:** The regulation of air temperature and humidity- heat/microclimate control.
- **Provision:** The evapotranspiration of soil and vegetation leads to a cooling effect, as the conversion of water from the liquid phase to the gas phase requires energy and thus the air temperature is reduced. The capacity of soils to deliver this service is closely linked to the water storage capacity, which depends on the soil texture, density, and organic matter.
- **Demands:** With climate change, this cooling effect will gain importance for the health of humans and other living beings.
- **Threats:** Soil degradation processes, such as sealing, compaction, and erosion, as well as the cultivation of inappropriate plant species, decrease the water storage capacity and thus threaten local climate regulation.

Global Climate Regulation
("the Carbon Cycle")

Definition: This soil ecosystem service refers to the ability of soils to maintain and potentially increase carbon storage in soils.

Outputs: Terrestrial carbon (C) storage, climate regulation and climate change mitigation on a global scale.

Underlying soil processes: Soil is an important C reservoir (2,700 Gt), containing globally more C than the atmosphere (780 Gt) and terrestrial vegetation (575 Gt) combined. This reservoir is controlled by the balance between soil organic matter accumulation and losses (soil C sinks and emissions back to the atmosphere). The C storage of soils is recharged by transferring C from the atmosphere via photosynthesis into plants and further as litter into soils. The persistence of C in soils is highly variable and depends on environmental (mainly climatic) conditions and land use. In particular, the soil fauna and microorganisms are responsible for the decomposition of soil organic matter. Among numerous physical and chemical soil properties, the texture, structure, pH, and nutrients (e.g. N availability) largely influence the amount, quality, and stability of soil organic C as well as the soil C sequestration potential. In general, an increase in soil C storage reduces atmospheric CO_2 concentrations and thereby helps mitigate climate change.

Interactions (synergies and trade-offs) with other SES: Soil C stocks are essential for almost all other services, in particular those that refer to agricultural production, water filtration and purification, nutrient cycling, and others.

Demand aspects: In order to mitigate climate change, this service is deemed to be of the highest importance.

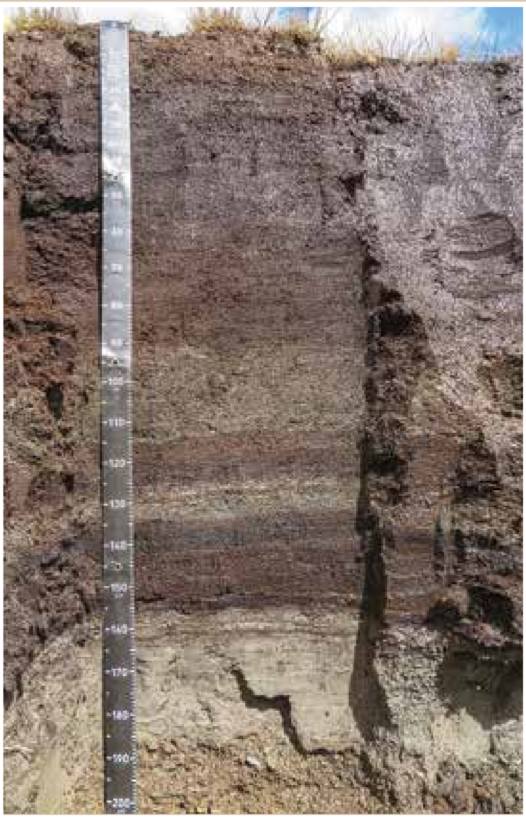
Land-use impacts: Land use heavily influences global climate regulation. For example, if forests are converted into agricultural land or settlements, this service is decreased (agriculture) or virtually lost (urbanization). Furthermore, the extraction of peat or the drainage of wetlands leads to an increase in CO_2 emissions.

The impact of climate change on provision of the service: Under a changing climate, the demand for the climate change mitigation effects is increasing drastically. In addition, in many ecosystems climate change may hamper carbon storage in soils due to warming and drying up.

Alps-specific aspects: Apart from the highest summits, which are largely free from vegetation and soil, the Alps are dominated by forest and grasslands, which feature relatively high soil carbon storage, albeit in the upper soil horizons, and therefore are very vulnerable to climate and land-use changes. Improved management of forests, grassland, and arable land can counteract the decline in soil carbon and even, if possible and reasonable, enrich the organic matter in the soils. Furthermore, the presence of concave areas stemming from glacial activity and the abundant precipitation in the Alps may result in extensive peatland where a large amount of C is stored. Like in other regions, a considerable share of such peatland has been strongly degraded by cultivation measures, also in recent decades. Nowadays, these areas are largely protected. When still under agriculture and cultivated, peatland may be a significant source of CO_2.

▲ **Figure 22:**
Histosol – organic matter rich soil formed from peat (Photo: S. Stanchi).

▲ **Figure 23:**
A carbon-rich soil with thick organic layers above limestone debris under a beech dominated stand at around 1500 m a.s.l.; Leutasch valley, Tyrol, Austria (Photo: C. Geitner).



◄ **Figure 24:**
Profile of the high elevated Rotmoos peatland at about 2300 m a.s.l. in the Rotmoos valley with typical changes of organic and mineral layers; Rotmoos valley, Tyrol, Austria (Photo: C. Geitner).

▲ **Figure 25:**
A Podzol soil profile, storing large quantities of organic carbon in deep horizons (Photo: M. D'Amico)

Global Climate Regulation ("the Carbon Cycle") in Brief

- **Output/effects:** Terrestrial carbon (C) storage, climate regulation and climate change mitigation on a global scale.

- **Provision:** Through photosynthesis, carbon (C) is withdrawn from the atmosphere and, via litter and root residue, stored as organic matter in soils. The C content is controlled by the organic matter input and its decomposition within soils. Globally speaking, soil stores more C than the atmosphere and terrestrial vegetation combined.

- **Demands:** In order to mitigate climate change with its negative impacts (e.g. global warming, permafrost degradation, droughts, enhanced runoff and erosion due to extreme weather events, etc.), regulating the global climate should be of the highest importance.

- **Threats:** Inappropriate soil management can result in greater C emissions than sequestration, which makes the soil a C source rather than a C sink.

Water Filtration and Purification

Definition: The soil ecosystem service water filtration and purification refers to the filtering of solid particles and retaining, degrading, and changing pollutants from water percolating through the soil. The result is clean ground and spring water that is fit for a specific use, e.g. for human consumption as drinking water.

Outputs: Clean ground and spring water, drinking water.

Underlying soil processes: The soil filters various particles and retains applied nutrients and pesticides, and organic and inorganic compounds (frequently contaminants), which usually originate from agricultural, municipal, or industrial by-products. The ability of a soil to mechanically filter particles is largely dependent on the size of the particles and voids and how fast water flows through the soil, while the chemical purification of precipitated water depends on interaction with active clay minerals, organic matter, and living organisms. The fate and transport of pollutants strongly depend on the neutralizing, buffering, and binding capacity of the soil, i.e. the specific ion adsorption, chemical degradation, and leaching processes they are subjected to. Soil compaction, contamination, and organic matter decline or the alteration of the composition of organisms, deplete the soil neutralization and purification capacities and accelerate the movement of polluted water through the soil into the groundwater – which is often an important source of drinking water.

Interactions (synergies and trade-offs) with other SES: For humans, the filtration and purification of water is one of the most important services that soil provides in our ecosystem. Even if soil largely provides this service, vegetation can support it in different ways, e.g. as an additional filter above the soil. Healthy soils are critical to ensuring clean water for consumption and food production.

All water cleaning processes are connected with the amount of percolation time and thus with the services of soil water retention and soil water storage. Furthermore, soil organic matter as well as biological activity (habitat provision) play a crucial role therein.

Demand aspects: Due to environmental problems and the growing world population, the societal demand for water filtration and purification will remain high, even if there is no clear link to climate change.

Land-use impacts: The capacity of soils to deliver this service is strongly influenced by land use and (unsustainable) soil management as they affect soil properties such as soil pH, soil organic matter content, and biological activity, and induce soil degradation such as erosion, compaction, and contamination.

The impact of climate change on provision of the service: In the course of climate change, higher temperatures and longer dry periods may affect the water uptake capacity of soils and are likely to decrease their organic matter content, which in turn quantitatively and qualitatively decreases the water filtration and purification capacity of the soil.

Alps-specific aspects: Many soils in the Alps are shallow and sandy, with high stone and low clay content, thus causing fast water percolation and thereby lower water filtration and purification capacities. Furthermore, Alpine soils tend to be more or less acidic (due to the high precipitation and not easily decomposable litter) and thus have reduced biological activity, which also decreases the filtration effects. The water filtration and purification capacities of the soils in Alpine valleys varies largely depending on the high/low clay or sand content.

▲ **Figure 26:**
Small mountain freshwater spring; water pouring from soil (Photo: M. D'Amico).

▲ **Figure 27:**
Water filtered and purified by soil feeds crystal-clear Alpine rivers; Savica waterfall, Slovenia (Photo: B. Vrščaj).

Water Filtration and Purification in Brief

- **Outputs:** Clean ground and spring water, drinking water.

- **Provision:** Undesirable substances are removed from water by infiltrating into and percolating through the soil. Physical, chemical, and biological processes, which are controlled by soil depth, soil texture, soil structure, the amount and quality of organic matter, pH, and the level of biological activity, contribute to this cleaning process.

- **Demands:** As the global population grows, the demand for clean water for personal use (e.g. drinking, domestic use) or agricultural and industrial use will also grow.

- **Threats:** The degradation of soils (i.e. heavy soil pollution, erosion, compaction, soil organic matter decline, soil acidification) threatens water filtration and purification.

Nutrient Cycle Regulation

Definition: The soil ecosystem service nutrient cycle regulation refers to the storage, exchange, and cycling of macro- and micronutrients and other elements with plants. The nutrient cycling service is based on major soil ecosystem services such as nitrogen fixation, phosphorus supply, and litter decomposition and mineralization. In addition, C sequestration is related to this service.

Outputs: The retention and cycling of nutrients for plants and soil biota.

Underlying soil processes: Besides the macronutrients (elements) derived from air and water (C, H, and O), the primary macronutrients are N, P, K, Ca, Mg, and S. The micronutrients, equally important but needed in small quantities, are: Fe, B, Mo, Cu, Mn, Zn, Na, Cl, Co, and Si. Decomposition by soil organisms is the key to nutrient cycling in soils. Decomposition results in nutrients that can become available to organisms (first of all, plants/crops). Decomposition is a complex process actually involving all soil organisms. Arthropods and earthworms fragment the material and mix it with the soil mineral fraction. Fungi and bacteria are very active in the decomposition process. Living organisms get energy or nutrients from the process. In general, compounds become simpler after each step. The portion of organic matter residue that is not broken down is then transformed into highly complex organic compounds (e.g. humic substances) that take a long time to break down and are important to soil structure and nutrient storage.

Microorganisms mediate nutrient availability through the decomposition of plant residue and soil organic matter and through nitrogen fixation.

Interactions (synergies and trade-offs) with other SES: Nutrients are essential for soil fertility, the most important and complex soil property. The availability of nutrients largely steers soil productivity and soil and aboveground biodiversity. For instance, in the same climate, the natural plant communities, as well as soil biota, vary regarding the availability of nutrients. In terrestrial ecosystems, nutrients are substantially concentrated in living biomass (plants) or in soil organic matter. Nutrient cycle regulation is a fundamental supporting service for agricultural and forest biomass production. In addition, this service is strongly linked to habitat provision, soil and aboveground biodiversity, and water filtration and purification (groundwater quality).

Demand aspects: Proper nutrient cycling, i.e. retaining nutrients in situ as much as possible, careful fertilization (i.e. the replacement of nutrients taken from the soil with crops), and protecting soil biota, are a substantial part of sustainable agricultural soil management practices. Nutrient cycling is crucial for the success of agricultural production in feeding the increasing global population.

Land-use impacts: Land-use (mainly for agriculture and forestry) and soil management practices, such as fertilizing, liming, and soil tillage techniques, fundamentally affect nutrient cycling, often by enriching the natural level of nutrients in soils. On the hand, nutrient-rich soils predefine the land use – mainly as regards agriculture.

The impact of climate change on provision of the service: The nutrient cycle may be affected in the course of climate change, as higher temperatures and more extended dry periods can hamper nutrient cycling, while pronounced rainfall can lead to leaching – i.e. the loss of nutrients from the root zone.

Alps-specific aspects: Especially in the upper, cool-humid forest zone, the slow decomposition of organic matter causes the accumulation of organic litter and thus thick organic layers. The nutrients in those organic layers are scarcely accessible to plants. In general, many Alpine soils feature favourable nutrient conditions due to the weathering and young soil development stage while Alpine floodplains are often richer in nutrients due to the influx of nutrients by waters and, in recent times, fertilization in agriculture.

▲ **Figure 28:**
Manure fertilisation returns plant nutrients back to the soil, increases soil organic matter content and stimulate the activity of the soil biota (Photo: J. Lesjak).

Nutrient Cycle Regulation in Brief

- **Outputs:** The retention and cycling of nutrients for plants and soil biota.

- **Provision:** Soil enables and regulates nutrient cycling in general. Thereby, nutrients are made available to plants and other biota.

- **Demands:** Rising demands for food and other plant biomass require an adequate availability of nutrients, well regulated nutrient cycling, and nutrient retention.

- **Threats:** Inappropriate (under- or over-fertilization – both unsustainable) soil management threatens nutrient availability, and can cause soil and groundwater pollution, e.g. through the leaching of nitrates and phosphorus to ground and surface waters.

Soil Habitat and Biodiversity

Definition: This particular soil ecosystem service refers to the ability of soils to provide an environment for many diverse organisms, where they can live and grow. There is great variability among soil organisms, from microorganisms (e.g. bacteria, protozoa), which are not visible to the naked eye, to meso-fauna (e.g. collembola), and macro-fauna (e.g. earthworms, insects).

The soil fauna is characterized by mutual interactions and it also interacts with the other organisms of the ecosystem in a very complex system. All of the soil organisms perform relevant ecosystem services and are crucial for healthy and productive soils, as they perform processes such as the decomposition of plant litter into soil organic matter and the mineralization of soil organic matter and release of nutrients. Biodiversity thus includes the variation of organisms and an abundance of genes that are vital to the ecosystem and human benefits.

Outputs: Biodiversity itself (from genes to organisms) and related benefits (e.g. species for medicinal purposes, the resilience of ecosystems to climate change, pests, etc.).

Underlying soil processes: Soil biodiversity is strongly determined by soil properties such as pore volume (a living space for soil organisms), the presence of water, air, and nutrients, the quantity and type of organic matter, etc., as well as inter- and intra-species relationships. Soil biodiversity is a dynamic property; it changes daily and seasonally as well as on a long-term basis due to climate change or soil degradation. It is difficult to record and compare the biodiversity of soils as it characterized by an enormous number of different groups of organisms and only some of them are sufficiently known. Thus, the evaluation of soil biodiversity is still subject to many uncertainties.

Interactions (synergies and trade-offs) with other SES: Both soil and aboveground biodiversity are steered/defined by soil properties, human interventions (i.e. agricultural or urban land use) and climate (change). The dominant role of soils in aboveground biodiversity is still not adequately recognized by the general public. Soil biodiversity is a characteristic of the quality of soil that affects the productivity and sustainability of agriculture production. It is also an important resource that regulates ecosystem processes. Nutrient-poor, shallow, or acidic soils attract a different range of plant, fungal, and animal species than soils rich in nutrients. Soil biodiversity affects and is a driver of many regulating services. Soil organisms decompose soil organic matter, store and cycle nutrients, decompose, degrade, or immobilize pollutants, control pests, etc. In general, the soil biota strongly contributes to the performance of other soil services such as agricultural and forest biomass production, water filtration and purification, and nutrient and carbon cycling and regulation. Soil abundant in "life" is highly valued as a gene pool.

Demand aspects: For climate change impact mitigation, high biodiversity is essential as it promotes the resilience of ecosystems. Responsible and sustainable soil management in agriculture as well as in other sectors has to protect the soil biodiversity, and is the key to healthy and productive soil and the performance of many important ecosystem services.

Land-use impacts: Soil biodiversity, as is the case with aboveground biodiversity, is primarily a result of soil properties and land use. Soil properties determine the abundance and diversity of soil organisms in soil itself, as well as the diversity and abundance of aboveground biodiversity. Soil and aboveground biodiversity are often drastically changed to meet human needs, for example, aboveground and soil biodiversity is fundamentally minimized due to agriculture (especially in the event of unsustainable soil management) or compromised by invasive alien species. Soil changes (fertilization or nutrient depletion, acidification, salinization, soil organic matter decline, etc.) and land use are reflected in both soil biodiversity and aboveground biodiversity. Sustainable agricultural and forest practices lead to increased soil and aboveground biodiversity.

The impact of climate change on provision of the service: In the course of climate change (i.e. higher temperatures and longer dry periods), soil properties also change, which affects soil ecosystem conditions. Thereby, they affect and/or change soil and aboveground biodiversity. Populations of specific soil species change or adapt to altered soil conditions or they vanish.

Alps-specific aspects: The wide range of topographic settings, geological substrates, local climates, etc., have resulted in a great diversity of soils and ecosystems in the Alps. Soils are usually shallow and slowly mineralize due to lower temperatures. This slow decomposition of organic matter is therefore a significant indicator of scarce microbial and fungal activity. The soil biodiversity can be reduced in forests due to forest monocultures, which increases soil acidity (e.g. pure spruce stands), and in agricultural land due to consequences of the conventional agriculture consequences (e.g. over-fertilization, ploughing).

◄ **Figure 29:**
Alpine soil is a home of an extreme number of different organisms (Photo: T. Peham).

▲ **Figure 30:**
The quite rare emerald green earthworm (Allolobophora smaragdina) is living in forests rich in deadwood; Brixen valley, Tyrol, Austria (Photo: C. Geitner)

▲ **Figure 31:**
Earthworms` burrows/channels from a soil depth of 60 cm in a dense Cambisol developed from till; Inn valley, Tyrol, Austria (Photo: C. Geitner)

▲ **Figure 32:**
High plant biodiversity in an Alpine grassland (Photo: M. D'Amico).

▲ **Figure 33:**
Peat bogs in the mountains are a valuable contribution to the biodiversity of mountain landscapes (Photo: B. Vrščaj).

Soil Habitat and Biodiversity in Brief

- **Output:** Biodiversity itself (from genes to organisms) and related benefits (e.g. species for medicinal purposes, the resilience of ecosystems to climate change, pests, etc.).

- **Importance:** Soil is a habitat for living organisms, a complex of biological communities, and a gene pool. Different soils offer different living conditions and steer the diversity and dynamics of populations of organisms. The abundance and diversity of populations of soil organisms ensure the performance of soil ecosystem services. It is difficult to record and compare aboveground and soil biodiversity as the latter includes a much greater range of different organism groups, only some of which are fairly known.

- **Demands:** Soil biodiversity is an aspect and indicator of soil health, and therefore of soil productivity. Thriving and resilient local environments, as well as the needs and well-being of humans and animals, require living, biodiversity-rich, and healthy soils.

- **Threats:** Soil sealing and unsustainable soil management in all sectors that negatively affect the living organisms in soil.

Cultural and Natural Archives

Definition: The soil ecosystem service cultural and natural archives refers to the ability of soils to preserve particular nature- or culture-related evidence that is invaluable as heritage. This also covers the existence of rare soils, as they allow the derivation of special natural or cultural soil-forming conditions.

Outputs: The preservation of the cultural and natural heritage.

Underlying soil processes: Soils with special nature- or culture-related properties have high potential to be applied for scientific purposes in order to obtain new and site-specific information on former environmental and land-use-related topics. In particular, the soils of wetlands and peatland, with their excellent conservation conditions due to oxygen exclusion and, moreover, their chronological stratification, are near-ideal archives for preserving remains revealing the natural and cultural history. Other valuable archives can be limnic or aeolian sediments, as well as paleosols. Apart from that, very different and sometimes specific soil-forming conditions, including former climate conditions and management practices, can lead to soils with prominent features, thus helping us to understand past and recent interrelations within the landscape.

Interactions (synergies and trade-offs) with other SES: Due to the wide range of possible soil features, the effect of this service on other SES is difficult to evaluate. However, if natural archives are to be preserved, the possible land-use activities, e.g. those related to agriculture or construction, are limited. Cultural artefacts, on the other hand, are often only found through such land-use activities.

Demand aspects: An understanding of the landscape and human-environment interactions can contribute to the development of a sustainable way of life.

Land-use impacts: The ability to maintain information on former environmental and land-use-related condition in soils can be threatened by some soil management practices, e.g. the drainage of peatland or deep ploughing.

The impact of climate change on provision of the service: In the course of climate change, higher temperatures and longer dry periods are likely to impair the conditions of wetlands and thus reduce their conservation ability. The biggest threat to the archive ecosystem service of other soils might be increased erosion risk due to more intensive rainfall events.

Alps-specific aspects: Due to the high diversity of both ecosystem and land-use types in the Alps, such archives can record this great variety of former and more current conditions. Therefore, soils in the

Alps are a very rich source for scientific and educational application, for instance by comparing current with former soil-forming conditions. Especially by examining peatland – but also other soils – the highly differentiated history of climate and landscape (including land use) in the Alps can be reconstructed. This can be done by investigating plant remains or special aspects of the local usage history, as several types of traces of human activity can be found in soils, e.g. artefacts, coal residue (fireplaces), or specific patterns in soils (e.g. indicating old pathways).

▲ **Figure 34:**
An uncommon feature of Alpine soils: Aeolian sediments overlying lime stone bedrock; Brixen valley, Tyrol, Austria (Photo: C. Geitner).

▲ **Figure 35:**
Soil excavation, presenting a more than 7.000 years old fire place on 2000 m a.s.l.; Fotsch valley, Tyrol, Austria (Photo: C. Geitner).

▲ **Figure 36:**
A close-up of coprolites, fossilized faeces, in soil organic matter – rich soil (Photo: M. D'Amico).

▲ **Figure 37:**
Micro-relief, soil and land-use related hot spots of Alpine grassland biodiversity; Isar valley, Bavaria, Germany (Photo: C. Geitner).

Cultural and Natural Archives in Brief

- **Outputs:** The preservation of cultural and natural traces.
- **Provision:** Soils with special nature- or culture-related properties have a high potential for scientific and educational application in order to obtain new and site-specific information. Wetland and peatland soils in particular are highly suitable as archives due to their ability to conserve remains under oxygen exclusion and chronological stratification, thereby revealing the natural and cultural history.
- **Demands:** An understanding of the landscape and human-environment interactions can contribute to the development of a sustainable way of life.
- **Threats:** Soil sealing, construction, deep soil tillage, and peatland drainage threaten such archives.

Recreational and Spiritual Services

Definition: Soil can serve as a ground for outdoor sports and tourism, enabling a wide range of activities and providing cultural, spiritual, and aesthetic experiences.

Outputs: Recreation, outdoor, and other leisure activities and aesthetic enjoyment; contributions to human health.

Underlying soil processes: Soil properties (e.g. texture, density, drainage) and site conditions (e.g. slope, morphology, vegetation cover, susceptibility to erosion) largely define the suitability of mountain soils for specific recreational purposes. For some activities, a specific type of soil management is required that changes the chemical and physical properties of the soil. For example, golf courses require optimal drainage and thus a specific soil texture, and must have continuous vegetation cover. Ski runs need levelled surfaces and soils adapted to long-lasting and high-density snow cover.

Interactions (synergies and trade-offs) with other SES: While the aesthetics of soil, as a part of the landscape, normally do not interfere with other soil ecosystem services, the use of soil as a ground for recreation may influence other relevant soil ecosystem services, such as water purification, surface runoff regulation, water storage, local climate regulation, and providing habitats (biodiversity).

Demand aspects: Many recreational activities are particularly relevant for the Alpine Region (e.g. skiing, mountain biking, hiking, etc.) and drive local economies. Alpine tourism has experienced an increase in visitor numbers in recent decades, partly caused by the increasing frequency of heat wave events in the lowlands. A better understanding of the impacts of sports and recreation on Alpine soils will help in formulating guidelines for their sustainable use and management in the tourism and recreation sectors.

Land-use impacts: Areas that are used for recreation are often simultaneously used as pastures (e.g. ski runs), forestry (e.g. mountain bike trails), or nature conservation (e.g. hiking trails). Hence, sustainable land and soil management must ensure the provision of a variety of soil ecosystem services. Another aspect is actively intervening in near-natural systems to improve their suitability for outdoor sport activities (ski slopes, mountain bike trails, etc.). These human interventions can severely affect the original physical and chemical soil properties through a variety of impacts due to machine-grading, trampling, or the use of heavy machinery, which in turn may affect the composition of the soil biota and influence the provision of other soil ecosystem services. Enhanced on- and off-site erosion can be a negative consequence as well.

The impact of climate change on provision of the service: Climate change is strongly affecting the vegetation belts and significantly changing the snow cover depth and duration at elevations below approx. 1,500 m a.s.l.. According to future scenarios, it is expected that ski resorts in the Alps will have to face climate warming and try to shift upward in order to maintain the snow cover for a sufficient number of months in the winter season. On the other hand, the rising temperature could shift the most common outdoor activities such as hiking to a higher elevation, thus increasing the demand for recreational services.

Alps-specific aspects: The Alps have a long history as a destination for recreation and tourist activities. At present, a significant part of all European travellers choose the Alpine Region as a holiday destination. In recent decades, skiing tourism has gained enormous dimensions. According to the 2019 International Report on Snow & Mountain Tourism, the Alps host 37% of the ski resorts and 80% of the major ski areas. The use of heavy machinery in the construction of ski slopes often significantly reshapes the morphology of the landscape, with consequent impacts on soil properties. The Alps have long been popular for hiking, which has led to a dense network of trails. In recent years, mountain biking has gained importance and many resorts have invested in mountain bike infrastructure. Those trails (hiking as well as mountain biking) are specifically built or have formed due to repeated passages, sometimes triggering soil degradation processes. Furthermore, in order to diversify the touristic offer in the Alps, quite a number of golf courses have been built, entailing significant changes in soil and vegetation.

▲ **Figure 38:**
Hiking in the Alps – as an important component of the landscape soils contributes to the recreation and spiritual experience; Fotsch valley, Tyrol, Austria (Photo: C. Geitner).

▲ **Figure 39:**
The scenic landscape of the Alps with its diverse patterns could not be possible without soils. Such spiritual experience is much needed to modern human; Fotsch valley, Tyrol, Austria (Photo: C. Geitner).

◄ **Figure 40:**
Nordic skiing in the Maritime Alps, Italy (Photo: S. Stanchi).

▲ **Figure 41:**
Number of visitors in mountains is increasing; the Julian Alps, Slovenia (Photo: B. Vrščaj).

Recreational and Spiritual Services in Brief

- **Outputs:** Recreation, outdoor, and other leisure activities and aesthetic enjoyment; contributions to human health.
- **Provision:** Soil provides the ground for recreation activities and tourism, thus enabling a wide range of outdoor activities and providing cultural, spiritual, and aesthetic experiences. For some activities, specific soil management is required, which changes the physical and chemical properties of the soil.
- **Demands:** Many recreational activities are particularly relevant for the Alpine Region (e.g. skiing, mountain biking, hiking, golfing) and drive local economies.
- **Threats:** Inappropriate management of infrastructure (e.g. ski runs and mountain biking and hiking trails) promotes severe erosion, which in turn threatens the provision of recreational services.

Imprint

What this is about

Soil is the basis of Alpine ecosystems; it is a fundamental natural resource especially in the vulnerable Alpine Region. Through the sustainable management and protection of soil, we enhance the sustainable management of the Alpine environment, considerably contribute to the performance and resilience of key ecosystem services, preserve biodiversity, and ensure the well-being of humans. Soil management and protection is provided for in the framework of the Soil Conservation Protocol of the Alpine Convention, which is aimed at safeguarding the multifunctional role of soil based on the concept of sustainable development.

About this book

This book presents a brief explanation of the main ecosystem services soil provides to the environment and humans within the different uses of land. The Soil Ecosystem Services for Decision-makers booklet is a contribution to activities aimed at raising awareness of soil and is intended for decision-makers who are not soil experts.

About the Links4Soils project

The Links4Soils project is focused on raising awareness of soils in the Alpine Region, reviewing the existing regional and national soil data, transferring knowledge and best management practices to policymakers, decision-makers, and other stakeholders, and promoting efficient soil protection strategies. Links4Soils aims to overcome existing gaps in soil-awareness, information, knowledge, and networking and to contribute to better implementation of the Alpine Convention Soil Protection Protocol.

Links4Soils project partners

Agricultural Institute of Slovenia, SI (project leader) • Office of the Tyrolean Provincial Government, AT • Autonomous Region of Aosta Valley, IT • Municipality of Kaufering, Department of Environment and Nature, DE • National Research Institute of Science and Technology for the Environment and Agriculture, Grenoble Regional Centre, Mountain Ecosystem Research Unit, FR • Slovenian Forest Service, SI • Institute of Geography, University of Innsbruck, AT • Climate Alliance Tirol, AT • University of Torino, Department of Agricultural, Forest and Food Sciences, IT

Acknowledgements

This project is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme.

WEB links

Links4Soils, an Interreg IIIB Alpine Space project: www.alpine-space.eu/projects/links4soils
Alpine Soils: alpinesoils.eu/

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