SOILGUARD

Sustainable soil management to unleash soil biodiversity potential and increase environmental, economic and social well-being

Grant Agreement no. 101000371

D6.2: Guidelines to implement interventions in which soil biodiversity acts as an NBS

WP	WP6 Conservation of soil biodiversity			
Author(s)	Alberto Martín Sánchez (UICN)			
Contributor(s)	Sauli Valkonen (LUKE), Tomas Van de Sande (INAGRO), Helle Hestbjerg (DTI), Merek Kesser (DTI), Zoltan Toth (MATE), Kerry Ryan (TEAGASC), Fiona Brennan (TEAGASC), Luis Daniel Olivares Martinez (UMH), Ina, Alsina (LLU), Agrita Švarta (LLU), María Paula Barral (INTA), Santiago Soliveres (UA), Daniel Johnson (IOW), Rochana Tangkoonboribun (TISTR), Rattana Ngamvisitsil (TISTR)			
Reviewer(s)	Darío Pollicino (UICN), Catherine Numa (IUCN)			
Deliverable nature	Report			
Dissemination level (Confidentiality)	Public (PU)			
Estimated indicated person-months	3			
Date of delivery	Contractual	31-01-2023	Actual	10-09-2024
Version	1.4			
Total number of pages	35			
Keywords	Soil biodiversity, Sustainable Soil Management, Nature-based Solutions			

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Document History

Issue Date	Version	Action
22/01/2023	V0.1	Initial version
29/01/2023	V1.2	Reviewed version
31/01/2023	V1.3	Final Version for Submission
31/08/2024	V1.4	Final Version for Submission after PR2 review

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Table of Content

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

List of Figures

List of Tables

List of Abbreviations

BE: Belgium

DK: Denmark

FI: Finland

HU: Hungary

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

IE: Ireland

LV: Latvia

ES: Spain

NbS: Nature-based Solutions

NCP: Nature Contributions to People

RTF: Rotational Forestry

CCF: Continuous Cover Forestry

SOM: Soil Organic Material

SSM: Sustainable Soil Management

TOC: Total Organic Carbon

SBWF: Soil Biodiversity and Wellbeing Framework

SENASA: National Agrifood Health and Quality Service in Argentina

DISTDYN: Forest management inspired by natural disturbance dynamics project

R&D: Research & Development

UNEA: United Nations Environment Assembly

FAO: Food and Agriculture Organization

IUCN: International Union for Conservation of Nature

Disclaimer

The misuse or erroneous external use of the materials that may emanate from this deliverable, either purposely in adapting the content or unintentional as transmitting in another language, are not the responsibility of the authors. The IUCN NbS programme is not directly involved in the creation or endorsement of this analysis. This document is not an official IUCN tool, it does not reflect the IUCN official position and any conclusions drawn from its application are the responsibility of the users. The content of this deliverable is the result of context-specific information, and there are limitations for the generalization of its conclusions.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

1. Summary

This deliverable aims to provide guidelines for implementing SSM (Soil Sustainable Management) practices, following the IUCN Global Standard for Nature-based Solutions (NbS). To achieve this, a global review was conducted on the implementation of SSM practices in diverse regions and their impact on soil biodiversity and biota to identify the extent to which well-managed practices promote soil biodiversity and to explore evidence regarding how other management practices, not explicitly considered in the studied sites, may influence soil biodiversity. Additionally, the results from the assessment of on-the-ground SSM practices conducted in T6.1, were analysed and summarized to develop recommendations to better integrate those practices and interventions within a NBS framework (see D6.1 for more information). The main barriers identified in the assessment for achieving a higher score for the defined criteria were also included. The results and insights from this work will be valuable for upcoming WP6 outcomes and will be further developed in the upcoming T6.1 and T6.2 activities.

2. Introduction

D6.2 Guidelines to implement interventions in which soil biodiversity acts as a NbS Soil Biodiversity assessment is one of the main results of the task *6.1. Develop recommendations and raise awareness among the conservation organizations*. It is a report on the soil biodiversity conservation and management recommendations on how implement SSM practices to be better aligned with the IUCN Global Standard for Nature-based Solutions (IUCN, 2020).

The document begins by providing a description of what Nature-based Solutions (NbS) are, exploring different definitions and their principles in Chapter 3. Chapter 4 contextualizes soil biodiversity and Soil Sustainable Management (SSM) practices, including a bibliographic review of the three practices considered in the project (organic farming, diverse mixed-species with low-fertilizer input in grasslands, and continuous cover in forest areas), as well as other management aspects influencing soil biodiversity. Chapter 5 incorporates barriers and recommendations identified in the assessment of on-the-ground SSM practices conducted in T6.1. Figure 1 illustrates the main activities carried out for conducting the assessment and designing the management guidelines.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

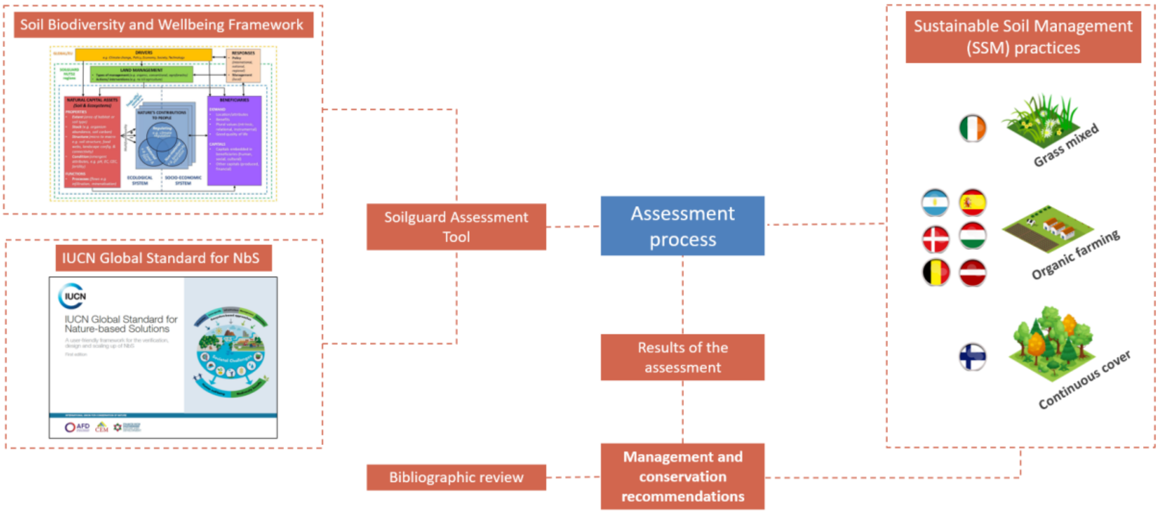

Figure 1. Diagram of the main activities carried out in T6.1 Develop recommendations and raise awareness among the conservation organizations

3. What are Nature-based Solutions?

Nature Based Solutions (NbS) is an umbrella concept that covers a range of different approaches that have emerged from a variety of fields, such as ecosystem-based adaptation, green infrastructure and ecological restauration. Some of these approaches have emerged from the scientific research domain, while others from practice or policy contexts. However, they all share the objective of enhancing the beneficial features and processes of ecosystems to address societal challenges, such as food security, natural disasters, or climate change.

More broadly, the development of the NbS concept has been grounded in the recognition of the linkages and interdependencies between people and nature, as well as an increasing understanding of the complexity of social-ecological systems. NbS acknowledges that biodiversity conservation and the protection of ecosystem services are critical for several aspects of human well-being.

The term NbS has been defined and used in a number of different ways. For example, the IUCN, the European Commission and UNEA have developed their own definitions of NbS, which, while broadly similar, have a few differences.

Table 1. NbS Definitions. Source: Own elaboration

Institution	Definition	Definition specificities
IUCN	Actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits (IUCN, 2020).	IUCN's definition emphasizes the importance of a well-managed or restored ecosystem as the foundation of any NbS.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

European Commission	Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions (European Commission, 2023c)	The European Commission's definition is broader and places more emphasis on solutions that are not only derived from nature but are also inspired and supported by it.
UNEA-5 resolution (United Nations Environment Assembly of the United Nations Environment Programme)	Actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits (UNEA, 2022)	UNEA's definition is very similar to IUCN's definition but more specific, emphasizing that NbS could have positive impacts in several ecosystems and must address economic and environmental challenges, in addition to addressing social and environmental challenges.

Despite their differences, each of the NbS definitions have a very similar approach and common strong points. It should be highlighted that all definitions consider that for an intervention to be considered an NbS, it must provide simultaneous benefits to the environment and human well-being. In addition to the NbS definition, IUCN also proposed a set of principles to provide a clearer understanding of NbS and facilitate its operational implementation (Cohen-Shacham et al., 2019). In this regard, Nature-based Solutions:

- embrace nature conservation norms and principles;
- can be implemented alone or in an integrated manner with other solutions to societal challenges;
- are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge;
- produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation;
- maintain biological and cultural diversity and the ability of ecosystems to evolve over time;
- are applied at the scale at a landscape;
- recognise and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services;
- are an integral part of the overall design of policies, and measures or actions, to address a specific challenge.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

4. Soil biodiversity and Sustainable Soil Management practices

4.1. Soil biodiversity

Soil is an ecological system rich in biodiversity that provides Nature Contributions to People (NCP) that are essential for human wellbeing. The complex and heterogeneous physical and chemical nature of soils across multiple scales provides a wide range of habitats for a multitude of organisms (Orgiazzi et al., 2016). From the smallest to the largest scales, numerous organisms interact to establish a limited number of associations that drive and regulate ecosystem functions and sustain ecosystem services. At each scale, soil organisms form distinct assemblages that live in specific niches, interact and carry out explicit functions (Orgiazzi et al., 2016). As a result, soil biota represents one of the largest reservoirs of biodiversity on Earth, particularly at the microbial scale (Yang et al., 2018).

Soil biodiversity is defined by FAO et al. (2020) 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 biota include bacteria, fungi, algae, protists, viruses, nematodes, acari (including mites), collembola (springtails), annelids (primarily earthworms), macroarthropods (such as spiders, ants and woodlice) and vertebrates (like voles, moles and shrews), and also the plants whose root exudates provide food for soil organisms in a zone around the roots known as the 'rhizosphere' (Larbodière et al., 2020). In SOILGUARD, we considered soil biodiversity by considering the abundance, biomass, and diversity of soil organisms, targeting prokaryotes (encompassing bacteria and archaea) as well as eukaryotes (including fungi, protists, nematodes, arthropods, and earthworms). However, an official and common definition of soil biodiversity is still lacking and this would be a significant step toward allowing soil life to enter into the legislative agenda for conservation (Orgiazzi, 2022). This definition is not trivial, considering, for example, that approximately three-quarters of all wild bee species and other arthropods nest and spend a significant portion of their life cycle on the soil and underground, during their larval stage (Antoine & Forrest, 2021).

The soil food web approach (**Figure 2**) provides a way to 1) describe soil biodiversity as an ecological network, 2) quantify its role in soil ecosystem functioning and 3) analyse the biological mechanisms underlying soil ecosystem functioning and the relationship between the structure of the soil biological community and soil ecosystem processing, as the food web interactions represent flows of matter, energy and information (FAO et al., 2020).

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

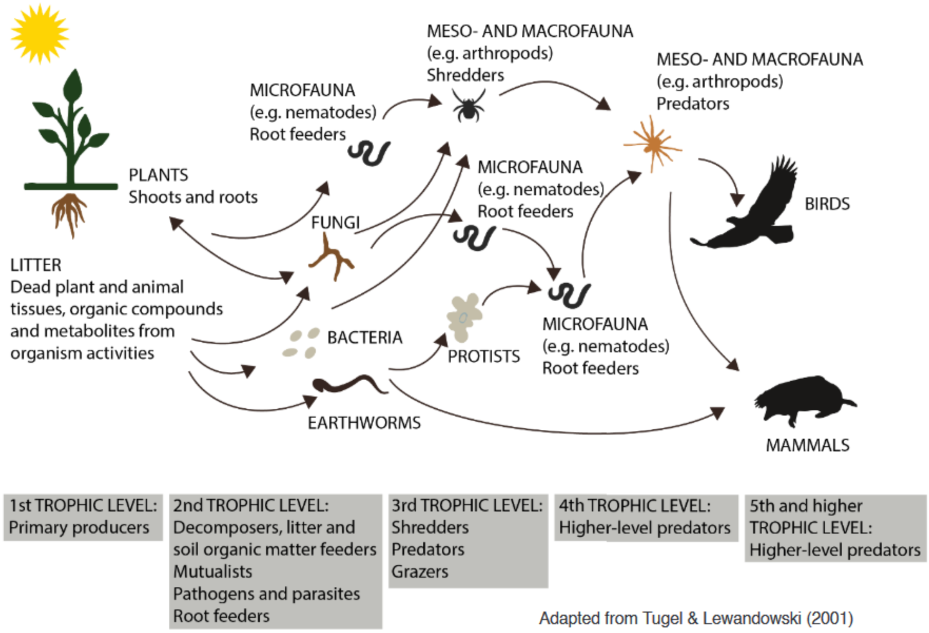

Figure 2. Soil food web representation, including possible feeding connections in a soil ecological community. Source: Larbodière et al., 2020

However, even if soil biodiversity exceeds that of other terrestrial systems by orders of magnitude and has a critical role in providing environmental services it is still undervalued and receives little recognition (FAO et al., 2020). Research on soil biodiversity has largely focused on the roles of specific groups of organisms, but knowledge of what biodiversity is actually present in soils in particular locations, and how soil species influence ecosystem functioning, is still scarce (Larbodière et al., 2020). The huge gaps in the documentation of soil biodiversity, especially of microorganisms, is a critical limitation to assess the conservation status of many soil biota. The 90-95% of soil biota remains unidentified and less than 1% of some groups has been described (Larbodière et al., 2020).

As represented in **Figure 3**, current data on soil biodiversity primarily revolves around plants and insects, with a notable deficiency in detailed knowledge regarding the conservation status and population trends of fungi, protists and collembola (Larbodière et al., 2020). Additionally, the IUCN Red List is not designed to assess the extinction risk of microorganisms since it relies on a set of quantitative criteria (such as population size, geographic range size, generation length as well as the nature of the threat facing the species) that are not appropriate criteria to assess the extinction risk of microorganisms. In this regard, it's worth mentioning that IUCN is currently working on a definition of soil dependent species for the use by the IUCN Red List of Threatened Species.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

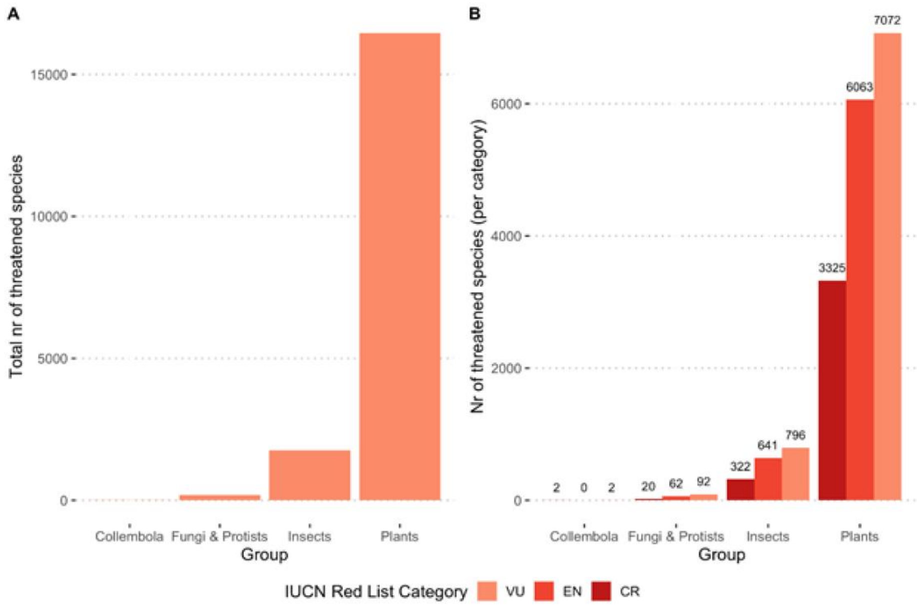

Figure 3. Number of threatened species by category according to the IUCN Red List. Categories: CR - Critically Endangered, EN - Endangered, VU – Vulnerable. Source: Larbodière et al., 2020

Soil organisms and their interactions play a crucial role in many ecological processes that support a wide range of NCP essential for human well-being (FAO et al., 2020; Orgiazzi et al., 2016). For instance, processes involved in soil structure modification and carbon and nutrient cycles, such as decomposition of organic matter and nitrogen fixation, are closely interrelated with the activities of soil biota (Larbodière et al., 2020). These processes benefit society by contributing to the delivery of 1) material NCP such as food and timber production 2) regulating NCP such as biological pest and disease control, soil erosion prevention, nutrient cycling, climate regulation, flood regulation and water quality regulation and 3) non-material NCP related to biodiversity conservation, tourism, aesthetic value, biodiversity education and abundance and diversity of weeds of conservation interest (FAO et al., 2020; Orgiazzi et al., 2016). Accordingly, the productivity of some ecosystems such as agroecosystems depends on the stability of the NCPs provided by the soil (Larbodière et al., 2020).

Soil biodiversity and its role in ecosystem functioning is under pressure due to some threats which has a negative impact on the delivery of several NCP (FAO et al., 2020). These include land-use change and intensification, pollution, soil erosion, compaction and sealing, acidification, wildfires, land degradation and desertification, climate change, the introduction of invasive species, acid rain and some agricultural practices and related processes, such as tillage, monoculture, removal of organic matter, pesticides and excess of fertilisers applications (FAO et al., 2020, Orgiazzi et al., 2016, Larbodière et al., 2020). There are important interactions among several of the threats listed above and the combination of factors may synergistically affect soil biota and its functioning. Unfortunately, the level of knowledge of the impacts of these threats on soil biodiversity and consequences for ecosystem functions are highly variable, depending on the threat and the region, as well as the target biota (FAO et al., 2020).

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Awareness and knowledge of soil biodiversity, its functional importance and how it respond to specific management practices are essential to better preserve belowground diversity and the important functions of these communities in order to enhance and maintain soil health (Orgiazzi et al., 2016, FAO et al., 2020).

4.2. Sustainable Soil Management

Sustainable Soil Management (SSM), is a management regime that maintain or enhance soil-related services without significantly impairing either the soil functions that enable those services or biodiversity (FAO, 2017). The Proposal for a Directive on Soil Monitoring and Resilience (European Commission, 2023), which was published in 2023 by the European Commission defines a list of sustainable soil management principles for Member States' consideration:

a. avoid leaving soil bare by establishing and maintaining vegetative soil cover, especially during environmentally sensitive periods;
b. minimise physical soil disturbance;
c. avoid inputs or release of substances into soil that may harm human health or the environment, or degrade soil health;
d. ensure that machinery use is adapted to the strength of the soil, and that the number and frequency of operations on soils are limited so that they do not compromise soil health;
e. when fertilization is applied, ensure adaptation to the needs of the plant and trees at the given location and in the given period, and to the condition of soil and prioritize circular solutions that enrich the organic content;
f. in case of irrigation, maximise efficiency of irrigation systems and irrigation management and ensure that when recycled wastewater is used, the water quality meets the requirements set out in EU regulation and when water from other sources is used, it does not degrade soil health;
g. ensure soil protection by the creation and maintenance of adequate landscape features at the landscape level;
h. use site-adapted species in the cultivation of crops, plants or trees where this can prevent soil degradation or contribute to improving soil health, also taking into consideration the adaptation to climate change;
i. ensure optimised water levels in organic soils so that the structure and composition of such soils are not negatively affected;
j. in the case of crop cultivation, ensure crop rotation and crop diversity, taking into consideration different crop families, root systems, water and nutrient needs, and integrated pest management;
k. adapt livestock movement and grazing time, taking into consideration animal types and stocking density, so that soil health is not compromised and the soil's capacity to provide forage is not reduced;
l. in case of known disproportionate loss of one or several functions that substantially reduce the soils capacity to provide ecosystem services, apply targeted measures to regenerate those soil functions.

These principles are important to define sustainable soil management. However, there are some aspects that could be further developed. Below are some suggestions to add to the principles in Annex III, based on scientific evidence.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

- Use of organic fertilizers in point 2 (e). The reduction of mineral fertilisers and use of organic fertilizers is key in the sustainable management of soils, as it significantly enhances soil biodiversity compared to mineral fertilisers (Heinen et al., 2023).
- Reduction of synthetic pesticides and organic pollutants as microplastics. Pesticides are a threat to soil health and their negative impact on soil biodiversity is well-known (Heinen et al., 2023). In the EU approximately 360,000 tonnes of pesticides per year have been used in the past decade, with no decrease (Heinen et al., 2023). Reducing pesticide use and risk remains a priority to ensure healthy soils. Moreover, organic pollutants affect the diversity and activity of soil organisms (Heinen et al., 2023), and especially microplastics in soil affect soil characteristics, microbial activity and soil flora and fauna (Heinen et al., 2023).
- Implementation of sustainable practices adapted to each context: Crop rotation, cover and companion cropping, mixed and intercropping, the reduction of synthetic pesticide and mineral fertiliser use, no/ conservation/minimal tillage, lower livestock densities, crop diversification, or the inclusion of landscape elements such as hedgerows and flower strips.
- Manage livestock density to prevent soil compaction and soil pollution through biocides such as antibiotics and antiparasitic agents present in manure: In soils that are subject to compaction, less intensive stocking of livestock can result in lower soil compaction and higher soil organic carbon and nitrogen in soils compared to intensive livestock management (Byrnes et al., 2018).

As agriculture is the main use of land (Eurostat, 2021), and intensive agriculture poses a threat to soil health (European Court of Auditors, 2019), promoting sustainable agriculture practices such as the ones listed above, could have a major positive effect for protecting soils in the EU. Such kind of approaches preserve and enhance soil health by implementing practices that promote functional biodiversity, and improve soil structure and organic matter (Oberč & Arroyo Schnell, 2020).

There are specific management systems and soil management practices that have relevant impact on soil biodiversity. This includes soil and land restoration, soil erosion prevention and control, afforestation and reforestation, bioremediation, sustainable land management and conservation, soil-oriented rewilding, and several sustainable agriculture approaches such as conservation agriculture, agroforestry, organic farming, and agroecology, among others (FAO et al., 2020; Orgiazzi et al., 2016). In the SOILGUARD project we have considered as SSM regimes the following:

- Organic agricultural management practices according to EC guidelines in farmland biome
- Diverse mixed-species with low-fertilizer input in grassland biome
- Continuous cover in forest biome

4.3. Sustainable Soil Management and soil biodiversity in SOILGUARD biomes

The following chapters include a bibliographic review of the three management regimes considered in the project (organic farming, diverse mixed-species with low-fertilizer input in grasslands, and continuous cover in forest areas), as well as other management aspects influencing soil biodiversity.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

4.3.1.Organic farming and croplands

Bengtsson et al. (2005) found positive effects of organic farming on species richness of all organism groups except non-predatory insects and soil organisms. Lori et al. 2017 showed that organic systems had greater biodiversity-related indicators than conventional systems.

Regarding soil animals, Bengtsson et al. (2005) references how soil animal densities were usually higher under organic agriculture even if variation in botanical composition, topography, crop yields and organic matter quality will also contribute to variation in soil organism densities independent of farming system. Although the number of studies is low in most groups, the results suggest that organic farming may enhance local densities of insect predators and soil fauna (Bengtsson et al., 2005). Results from these studies suggest that positive effects of organic farming on species richness are anticipated in intensively managed agricultural landscapes but such effects may not be evident in small-scale landscapes. Therefore, measures aimed at preserving and enhancing biodiversity should be more tailored to the specific characteristics of landscapes and individual farms than is currently practiced.

Kendzior et al. (2022) present a very comprehensive report about how crop production practices (such as land use, tillage, agroecosystem crop diversification (which includes plant diversity, crop rotations, cover crops), crop residue management, plant variety selection, irrigation, fertilization and pest management), impact on the soil microbiome.

In general, land-use intensification and high -input agriculture, particularly tilled agroecosystems with narrow crop rotation/short fallow management decreases the abundance and community diversity of soil biota and in contrast, management characterized by rotations, no-tillage, organic amendments and maintenance of non-productive elements are found to be linked to soil health (higher soil respiration and water-stable aggregates), greater soil fungi, mycorrhizae, and Gram negative bacteria (Lynch, 2022 and Mann et al., 2019) and an increase in species richness and overall density (Brussaard et al., 2007).

Greatest benefits to soil biota activity and diversity, particularly over the long term, are likely to come from the proper choice of crops and trees and their distribution in space and time, the enhancement of natural pest and disease resistance of crops, the improvement in the quality of residues produced, and management of organic matter and other external inputs into the system. Minimum tillage and maintenance of crop residue cover on the soil surface also benefit belowground food webs and processes compared with conventionally cultivated soils (Brussaard et al., 2007).

Hawes et al. (2018) showed that integrated cropping systems enhance biodiversity and reduce environmental impact without compromising crop yields. Integrated cropping practices included conservation non-inversion tillage to a depth of 7 cm, organic carbon amendments, integrated pest and weed management and reducing crop protection inputs, incorporating cereal straw, cover crops legume intercrops, and sowing field margins with a species-rich mix.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Pesticides have been widely shown to have several negative impacts on soil biota (Larbodière et al., 2020). Lori et al. (2017) shows that even if organic pesticides are still widely considered to be less harmful to the environment than synthetic products, differences in microbial activity and community abundance were not impacted by different kind of pesticides which indicates differences in pesticide effects to be rather weak or pesticide-effects themselves to be short.

Management practices such as reduced-tillage, cover crops, crop diversificationa and legume crops in rotations increase soil microbial activity in general, and microbial biomass and diversity in particular, increasing microbial biomass, mycorrhizal fungi, and soil fauna, even if it is not as clear how beneficial these management practices are under semiarid agroecosystems (Ghimire et al., 2014).

Combinations of organic amendments and perennial legumes in rotations, which are common practices in certified organic crop and forage production can shift microbiotic properties toward N-limited conditions that favour fungi. (Ghimire et al., 2014). However, Venter et al. 2016 showed that diverse crop rotation to have a positive effect on microbial richness and diversity though inclusion of legumes did not specifically affect microbial community structure. On the other hand, Garland et al. (2021) showed that crop diversity had a relatively minor effect on soil microbial diversity, soil multifunctionality and yield and in contrast, the proportion of time with crop cover (including cash crops, cover crops or forage leys) during the past ten-year crop rotation had a much stronger impact.

Regarding cover crops, the meta-analysis developed by Shackelford et al. (2019) pointed out that even if in plots with cover crops, there was 41% more microbial biomass in the soil, compared to control plots with bare soils or winter fallows, they did not find enough data to quantify the effects of cover crops on biodiversity conservation. However, if cover crops increase the plant or habitat diversity of a field, whether in space or in time, then they might also increase the biodiversity of the farm.

In a more recent research, Yousefi et al. (2024) showed that compared to monocropping, in general, cover cropping enhances soil biodiversity. Cover crops have an overall positive effect on soil biodiversity indicators, including total bacteria and fungi, soil microbial abundance, and activity and biomass. Specifically, habitat provision for soil biodiversity consistently stands out positively, with cover crops demonstrating an overall enhancement of soil microbial abundance, activity, and diversity. However, the effect of cover crops on microbial biomass depends on residue management practices, tillage, soil texture and cover crops species, among other factors.

The abundance of microarthropods generally decreases with increased tillage, and it has been also shown that earthworm abundance, biomass and species diversity decrease significantly with higher tillage intensity (Larbodière et al., 2020). Intensive tillage drives the mineralization of labile soil organic matter and shift properties toward C-limited conditions that favour bacteria and reduce soil organic matter concentrations, while reduced tillage conserves labile substrates and creates a more consistent soil environment for microbial activity and fungal and bacterial growth (Ghimire et al., 2014). However, how tillage impacts soil fungi is less clear and it can has positive or negative impacts (Larbodière et al., 2020). Briones & Schmidt. (2017) showed that no-till and conservation agriculture significantly increased earthworm abundance and biomass compared to when the soil is inverted by conventional ploughing. Long-term reduced tillage and no tillage practices have been identified to positively act on microbial indicators such as fungal hyphae length, and fungal abundance (Lori et al., 2017). Lori et al. 2017 also found that organic farming systems had greater soil microbial biomass and linked enzyme

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

activities than conventional systems attributable to crop rotations and use of organic amendments. Li et al. (2020) also showed that the response of microbial parameters to conservation tillage practices is consistently positive for simple parameters such as soil microbial count but context dependent for more complex parameters such as soil microbial diversity and community structure. The study developed by Mathew et al. (2012) highlighted that tillage practice and soil depth were two important factors affecting soil microbial community structure and activity, and conservation tillage practices improve both physicochemical and microbiological properties of soil. Additionally, results from Legrand et al. (2018) showed the importance of tillage for both bacteria and fungi, with species richness and evenness significantly higher in fields under minimum tillage practices than in fields under conventional tillage.

Additionally, margin strips in arable systems is a practice that support larger earthworm populations than are found in-field, but field margins did not appear to enhance in-field populations (Roarty & Schmidt, 2013). Bengtsson et al. 2005 found that in mosaic landscapes characterized by a high proportion of non-cropped areas, research found that organic farming did not have a discernible impact on diversity or species richness. Therefore, positive effects of organic farming on species richness and diversity are more likely to be observed in intensively managed agricultural landscapes rather than in small-scale mosaic landscapes with a mixture of agricultural fields and non-cropped habitats.

Furthermore, differences in microbial size and activity between organic and conventional farming systems vary as a function of land use (arable, orchards, and grassland), plant life cycle (annual and perennial) and climatic zone (Lori et al. 2017).

In general terms, when designing where to prioritize interventions it is relevant to consider that changes of the system at the highest level (e.g. the cropping system) will influence all the other levels of management, and will generally lead to more rapid system responses than changes at lower levels (e.g. organic matter management, tillage, soil fauna or microbial inoculation) (Brussaard et al., 2007). Therefore, interventions at highest levels are likely to higher impact than those at lower levels that affect soil fertility and plant production mostly indirectly.

When analysing wider management systems over the beyond the practices, there are many different ways to farm more sustainably that are already in use around the world including agroecology and regenerative agriculture among others. (Larbodière et al., 2020). In this regard, regenerative agriculture could be highlighted, as it is an agricultural production system specifically focused on enhancing and sustaining the health of the soil (Oberč & Arroyo Schnell, 2020). Specific management practices may include cover crops, reduced tillage, diversification of crops, soil organic amendments, mulching, and avoiding land use conversion (Doran & Zeiss, 2000; FAO et al., 2020; Orgiazzi et al., 2016).

4.3.2.Grass mixtures with reduced inorganic fertilization and grasslands

There is evidence that increasing plant diversity results in positive cascades on microbial abundance, diversity and activity of belowground microbial communities across multiple systems (Lange et al., 2015) and plant community had a stronger effect on fungal community composition than on prokaryotic community composition (Ryan et al., 2023).

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Monoculture systems in grasslands can reduce the diversity and abundance of other organisms within ecosystems, including a reduction in the diversity and abundance of soil microorganisms and soil invertebrates (Plantureux et al., 2005) and plant species diversity can increase the abundance of soil microorganisms and soil invertebrates in semi-natural and natural grasslands (Eisenhauer et al., 2013; Zak et al., 2003; Loranger-Merciris et al., 2006).

Loranger-Merciris et al., 2006 shows that culturable soil microbial activity and diversity declined with declining plant diversity and that changes in plant diversity and composition in grassland ecosystems lead to a rapid response of bacterial activity and diversity. Ryan et al. 2023 showed that microbial abundance was not significantly influenced by plant community type across the entire soil depth profile in grasslands, but prokaryotic community composition was significantly influenced by plant community in the top 15 cm of soil, and fungal community composition was significantly influenced between 15 and 30 cm in depth.

Considering the effects of specific grass species and taxonomic groups, Zhao et al. 2015 showed that biomasses of total microbes, bacteria, fungi, and green alga were significantly greater under legume monoculture than that under grass monoculture; and fungal biomass was significantly greater under grass-legume mixed culture than under grass monoculture in wet conditions. Specifically, legumes benefit bacterial-mediated decomposition more than fungal-mediated decomposition because nitrogen-enriched litter is more accessible to bacteria than to fungi. Moreover, soil microbial community structures did not show significant differences among the three planting systems in dry conditions.

Zhao et al. 2015 gather information about how the presence of legumes in grasslands increased soil microbial biomass and activity, the abundance of bacterivorous nematodes, the abundance of mites and omnivorous, and the diversity and density of earthworms. Moreover, legumes increased the complexity of soil food webs, as indicated by an increase in the number of trophic links and multi-trophic interactions (Zhao et al., 2014). Also, a density effect of legumes on soil microbial communities was identified suggesting that a higher density of legumes may cause a greater effect on soil microbial communities (Zhao et al., 2015). Ikoyi et al., 2023 pointed out that multi species forage sward mixtures that include grasses, legumes, and herbs can have a positive effect on the soil nematode community and nematode-based soil quality indices.

Ryan et al., 2023 showed that deep rooting plants may therefore open new microbial niches at depth and lead to greater utilization of available resources in the deep soil environment. These results indicate the potential for using deep rooting plant species in agricultural grasslands as a targeted management practice for enhancing soil biodiversity in new niches.

The grass species may also affect soil microbial community. Bhandari et al., 2018 showed that the combination of bluestems growing with alfalfa had a more positive impact on the soil microbial community in comparison to bluestems, alfalfa alone, and native mixed-grass pastures

Regarding fertilization, Zhao et al., 2015 showed that the biomasses of total microbes, bacteria, and green algae were significantly higher under moderate N fertilization compared to low N fertilization and green algal biomass was significantly greater under high N fertilization than under low N fertilization during the wet season. However, there were no significant differences in both biomass

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

and diversity of the microbial community among low, moderate and high level of N fertilization. Specifically, there are conflicting results concerning the effects of inorganic nitrogen application on microbial soil microorganisms (Zhao et al., 2013) but several studies have indicated that organic fertilization increases species richness and abundance, enhances food web complexity in grasslands (Bengtsson et al., 2005; Zhao et al., 2015).

Regarding the effects of fertilisation in earthworm abundance in a semi-natural grassland area, Timmerman et al. 2006, showed that there are no statistically significant differences were observed between the farmyard manure and no fertilization treatment but slurry manure had a lower earthworm abundance than farmyard manure and no fertilization treatment. Dhakal & Islam, (2018), showed that the application of chemical N fertilizer decreases fungal biomass and fungal-bacteria ratio in soil because it renders the bacteria to become more competitive.

If species are lost due to a long history of overgrazing they may not return even when grazing intensity is reduced and reseeding may be needed to improve plant species diversity (Reed & Morrissey, 2022). Several aspects should be considered to design a diverse forage seed mixture: seasonality, light requirements, drought tolerance, root structure, plant height and form, life strategy, nutritional qualities, and disease susceptibility and be at least mildly palatable for livestock. (Reed & Morrissey, 2022)

4.3.3.Continuous cover and forest areas

Forest clearing reduces vegetation biodiversity and habitat variability while increase environmental homogenization compared to continuous cover (Xu et al., 2015), which have great potential to enhance conservation at landscape and regional scales causes more opportunities for understorey species and can promote niche differentiation and increase environmental heterogeneity (Edwards & Laurance, 2013). These two logging regimes have different effects on soil microbial diversity (Xu et al., 2015). However, continuous cover also has a relevant impact on ecosystems, even if this management system have a much lower negative effect on measured biodiversity responses, and retains a high richness of forest taxa (Gibson et al., 2011). In this regard soil biodiversity and related ecosystem processes may be affected after even very-low, reduced-impact logging intensities (França et al., 2017).

Continuous cover forestry has been proved to provide higher habitat availability for indicator species dependent on deciduous and large trees and mature forest structure, to have higher multifunctionality and biodiversity indicators yielded higher values under this management system (Peura et al., 2018). In general, continuous cover is less harmful than clearcutting and may provide more habitats and resources for species living in mature or late successional forests, invertebrate species, soil fauna and dead wood dependent species (Peura et al., 2018).

Although old-growth specialists tend to disappear from clear-cuts, local invertebrate species richness may increase as forest generalists persist and numerous open-habitat species, not directly associated with the characteristic micro-habitats of old growth, appear However, at the landscape or biogeographical scale intensive logging tends to homogenize forest habitats and lead to declines of sensitive species (Niemela, 1997).

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Clearcutting logging has been shown to impact the species composition of the ectomycorrhizal fungal community rather than reducing its abundance (Jones et al., 2013). Chen et al. 2021, also suggested that selective logging is better than clear-cutting for conserving soil fungal diversity even if the changes in tree species due to selective logging has a significant influence on the fungal communities and on the genetic relatedness and diversity of fungal species across different spatial locations.

In general terms, other issues should be considered when analysing the impact of different forest management options in biodiversity. França et al. (2017) recommended the establishment of multiple spatial scales for timber extraction to improve the sustain ability of tropical forest management, due to biological consequences from impacts are highly dependent on the scale at which impact is measured. Niemela (1997) also mentions that diversity should be preserved on all scales and that from the management perspective, the stand and landscape levels are crucial, as they represent the scales at which forestry typically operates.

Regarding the intensity of the logging, there are several studies that identify that a higher intensity of timber harvesting result in higher impacts in biodiversity (Peura et al., 2018; Heinonen et al., 2017; Eyvindson et al., 2018; Triviño et al., 2017) and even small interventions in the forest can have a significant impact on biological diversity (França et al., 2017). Also, careful forest management planning may reduce the trade-offs between biodiversity and the economic performance, but it is not possible to achieve high levels of biodiversity if the objective of forest management was to maximize timber harvest revenues because there are strong trade-offs between provisioning timber and biodiversity (Triviño et al., 2017). However, small reductions in timber revenues, it is possible to greatly increase the multifunctionality of the landscape, especially the biodiversity indicators (Peura et al., 2018). In this regard, closer-to-nature forest management (European Commission, 2023b), offer a framework to promote biodiversity-friendly and adaptive forest management.

Additionally, there is a clear association between dead-wood volume and biodiversity (Gao et al., 2015). Since dead wood and coarse woody debris and large deciduous trees are two characteristics of the old-growth forests that provide microhabitats for many specialist species, such as arthropods, they should be maintained and enhanced by forest management (Niemela, 1997). Peura et al. 2018 pointed out that both continuous cover and clear-cutting practices only provided approximately 25% of the desirable minimum level of dead wood. Therefore, there is room for improvement in both management regimes. Additionally, undisturbed old-growth forests could be maintained to sustain several species and to serve as sources for recolonization Niemela (1997).

Partial retention of legacy trees and protection of refuge plants, as well as preservation of the forest floor, can maintain mycorrhizal networks providing fungal inoculum, support soil food webs, and promote biodiversity (Simard et al., 2021).

Even if continuous cover forestry has greater potential to maintain multifunctional forests, continuous cover forestry was not the best management system for all ecosystem services or biodiversity indicators, considering the habitat needs of early successional species (Peura et al., 2018). In this regard, the combination of different forest management practices provided higher levels of services and indicators than single practices, so using a diverse set of silvicultural practices could be also explored (Peura et al., 2018). Triviño et al. (2017) also suggest that a combination of forest

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

management regimes is needed to obtain the maximum ecosystem services and biodiversity indicators.

5. Recommendations identified in the SSM assessment

Within T6.1, the specific SSM practices implemented in the different regions were reviewed using the UICN Global Standard for Nature based solutions and evaluated using an assessment tool. This assessment tool has also been used to identify barriers and recommendations for better integration of these practices and interventions within the NbS framework (see D6.1 for more information).

This section describes the barriers identified that prevent each criterion from being met to a greater extent and recommendations to better integrate those practices and interventions within a NBS framework. It should be noted that the topics addressed in the IUCN Global Standard for NbS, which were thoroughly examined in other WPs (WP2, WP3, and WP4), have been developed with more detail.

5.1. Influences and impacts

5.1.1. SSM practices respond to the current state of the ecosystems and soil biodiversity

Conducting in-depth studies about the state of ecosystems and soil biodiversity is crucial for informing the design of SSM. These studies should go beyond local scales and embrace broader regional and national perspectives, rather than being limited to specific farm or field locations. The analysis should include information about the drivers of change and biodiversity loss and a detailed identification of requirements to maintain or recover ecosystem integrity.

Efforts to coordinate funding for comprehensive, large-scale research are essential. This research should focus on monitoring ecosystems and biodiversity across various trophic levels and ecological groups. Human and economical resources need to be allocated to collect data and establish a specific knowledge base that is verified at the local scale, serving as a foundation for the development of SSM and support farmer advice. Analyse management systems with production cycles exceeding 5 years under the same regime; aiming for durations between 15 and 20 years is desirable, with durations longer than 30 years considered ideal. In this regard, the time and spatial scale of the analysis is crucial. Stakeholder engagement and communication should be taken into account, to increase public understanding about the relevance of these analysis, as well as gathering input and feedback to ensure the assessment is socially, economically and politically relevant

Heterogeneity in ecosystem status, soil biodiversity, and the combination of SSM practices poses a high level of complexity when providing recommendations, since recommendations should be specifically adapted to each context. In this regard, specific funding is essential for sampling, laboratory analyses, and addressing logistical challenges associated with collecting a representative number of soil samples. Various practices in different contexts should be covered in order to facilitate the extrapolation of results more comprehensively.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Additionally, increasing awareness can lead to expanded resources for soil biodiversity research and foster political discourse on the detrimental impacts of practices like clearcutting, and on the opportunities to address these impacts though SSM practices, like continuous cover forestry. In croplands, there is a need for increased research into the effects of soil biology, physical, and chemical properties on soil nitrogen dynamics. Additionally, there should be a focus on translating this research into practical and tailor-made advice that is understandable to farmers.

5.1.2.SMM practices recognises and responds to the interactions between the economy, society and ecosystems and integrate complementary interventions

One of the main barriers to better fulfilling this criterion is the absence of data and information about the relationship between SSM and social, economic, and environmental elements and dynamics, specifically SSM impacts. Limited previous research has been oriented to understand the economic and cultural relationships with SMM practices and NCP, but there is a general lack of information.

Synergies across sectors should be thoroughly investigated, and all relevant complementary interventions within and surrounding the intervention area should be integrated within SSM practices and revisited for in the decision-making process throughout the intervention timescale.

Transdisciplinary research is essential to streamline the collection of outcomes related to how the economy, society, and ecosystems influence agriculture and organic farming. Mechanisms are needed to facilitate the compilation and dissemination of new data and research findings concerning the economy, society, and ecosystems, and their integration into farming decision-making processes. Collaboration among research organizations, policymakers, farmer cooperatives, farm advisory services, and farmers is crucial.

In croplands, the precise determination of interactions and synergies remains unresolved. At an economic level, the higher prices associated with organic products are considered by a significant portion of consumers, constraining the expansion of organic production in competition with conventional alternatives. In this regard, management practices should extend beyond production and integrate distribution and access to the products. Additionally, specific infrastructure is needed for recognizing the interactions between the economy, society, and ecosystems and integrating complementary interventions for reducing nitrate leaching or erosion. For example, reducing erosion requires tailored cultivation practices and accessible machinery. To achieve a reduction in nitrate leaching through SSM practices, the facilitation of soil nitrate measurements is essential for obtaining a detailed understanding of soil nitrogen dynamics. Long-term studies with heat wave and drought simulations should be also conducted to gather more data.

In forest ecosystems, the needed time for identifying and elaborate a response to interactions and integrate complementary interventions takes much more time than in crop systems, with a time scale of several decades. Stakeholder reluctancy to admit the weaknesses of RTF and the need to establish balances between complementary approaches and interventions is one of the main barriers to better achieve this criterion.

According to the findings in D3.2, maintaining multiple ecosystem functions simultaneously at high levels within a specific agricultural management framework can be challenging. This may indicate that

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

adopting a mosaic of different management systems could potentially enhance soil functions at a landscape level. Diverse management practices across space and time could serve as a viable approach to address these interactions

5.1.3.Risks and trade-offs are identified, managed, and inform corrective actions and safeguards

Addressing internal risks requires additional research on a regional scale and the implementation of large-scale structural measures to mitigate risks associated with land management. The incorporation of resilient theories and climate change adaptation practices in agriculture and forestry provides an opportunity to integrate risk management into farming decision-making processes. There is a need to continue promoting the use of meteorological monitoring schemes and early warning systems, along with securing financing for soil monitoring campaigns and social observatories.

While risk drivers may be well identified, the consequences and risks associated with the large-scale implementation of organic crop production remain unclear, both at local and global levels. A noticeable lack of data and studies on the long-term risks and trade-offs of organic farming exists. Even though farmers are well aware of the mitigating effect their soils can have on risks, primarily related to weather, pests, and diseases sometimes there are doubts about optimal management practices, such as the depth, type, and intensity of tillage in relation to the technical aspects of crop rotation.

In this regard, there is a lack of knowledge and practical experience among farmers, landowners, and professionals. Capacity building on CCF, coupled with the promotion of an open-minded attitude rather than maintaining the adherence to defunct paradigms, is essential. Additionally, the results of research an innovation projects should be aggregated and distributed in a farmer-friendly format. Specific actions should be taken to initiate conversations with and among farmers, openly exploring the risks and benefits associated with organic soil management. The information gathered should then be communicated back to advisors and researchers, enabling policymakers to make well-informed decisions.

The possible risks of undesirable changes and their drivers are identified, taking into account scientific and local knowledge and the management of these risks should be integrated into the design of the SSM. Possible adverse impacts of SSM interventions on ecosystems, ecological process and species should be identified and mutually agreed upon limits of trade-offs are in place and documented. Risk management should include the definition of safeguards that should be triggered if the trade-offs thresholds are exceeded, with clear documentation provided.

5.1.4.SSM must address societal challenges that have been identified, thoroughly understood, and well-documented

There are still significant knowledge gaps due to insufficient documentation and a lack of context-specific information about societal challenges at the local scale. This is particularly notable considering that the main challenges may differ at various scales. The most pressing societal challenges should be prioritized based on full consultation with beneficiaries. The drivers of and responses to identified societal challenges should be understood, referenced to the relevant national/local context, and fully documented. Collaborating with government agencies dedicated to social and agrarian analysis could

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

be a strategic approach to generating a diagnosis of challenges related to the implementation of SSM practices and the monitoring of soil biodiversity.

Regarding climate change impacts, preliminary results included in D3.2 shows relatively weak support for the buffering impact of organic management to mitigate the negative impacts of future climatic scenarios on soil functioning.

With the advancement of European biodiversity monitoring legislation, more appropriate metrics could emerge in the near future. In this regard, there is a need of funding and human resources to deploy an edaphic biodiversity monitoring campaign on an adequate scale.

A more comprehensive research approach is needed to investigate the effects of SMM practices, particularly focusing on organic fertilizers and pesticide-free methods, in relation to soil biodiversity loss, land degradation, and climate change impacts at local level, among other societal challenges. It would be also recommendable to conduct comparisons with various farming practices, such as conventional methods, reduced tillage, no-till, grazing, and annual versus perennial systems, to assess discernible differences and generate a comprehensive diagnosis of challenges related to the implementation of SSM practices and the monitoring of soil diversity.

5.1.5.SSM practices have a positive impact on soil biodiversity and ecosystem integrity and the impact is periodically assessed

The results included in D3.2 shows that the different sites harbour a unique soil biodiversity, with the factor site explaining 54-75% of the variance in the data of alpha and beta diversity. Management effects significantly influenced all three groups of the soil biota but explained only around 2% of the variability. However, these management effects were highly site-specific, with the interaction between site and management explaining around 10% of the variability.

Fungal and eukaryotic communities seem to be less responsive than prokaryotes to site, management and drought as a whole. Results indicate that shifting from conventional to organic agriculture will have detrimental effects on N-related bacteria and collembola. However, generally positive effects are expected for general biological activity (N mineralization, enzymatic activities), and fungi (including mycorrhizae) communities. There are several neutral or negative effects in faunal and other eukaryotic groups. These results, together with the prokaryotic biodiversity, indicate that more in-depth analyses are needed to identify taxonomic groups that respond to the combined effects of management and drought. Overall, D3.2 shows that each site should be taken individually to assess the effects of climate change and management on soil biodiversity.

Regarding ecosystem integrity, results included in D3.2 also showed that sustainable management generally enhances soil functionality, especially in cropland areas with low initial organic carbon, where the potential for improvement is greatest. The experimental sites with the highest soil organic C levels showed the least positive effects of sustainable soil management. The latter result supports the notion that organic agriculture and other soil sustainable management approaches and techniques may be more beneficial in places with relatively low organic carbon levels (either under more arid conditions and/or in more degraded soils) and therefore with a stronger potential to enhance soil carbon storage.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Little evidence was found in favour of, or against, conversions from clear cutting to continuous cover forestry on forest areas and from grass monoculture to grass mixtures on grasslands.

The implementation of data collection and documentation processes on soil biodiversity, its impact, and the management practices that facilitate its proliferation, at short and long term and at different spatial scales are significant processes that would facilitate a higher fulfilment of this criterion. Governmental institutions can lead the implementation of these monitoring activities once the European and national regulatory frameworks are defined, while maintaining collaboration with researchers and decision-makers. Additionally, the SSM outcomes related to biodiversity and ecosystem integrity lack specificity.

5.1.6. SSM practices have a positive impact on human wellbeing and the impact is periodically assessed

The results presented in D3.2 show that sustainable soil management generally benefits soil functioning, which may have an indirect impact on human well-being. These results suggest strong benefits of shifting from conventional to organic agriculture in croplands, with little evidence in favour of, or against, similar conversions on forests or grasslands. Sustainable management showed strong benefits for ecosystem functioning, particularly pronounced in our cropland sites with generally low initial soil organic carbon.

However, it has been identified that there is insufficient research specifically addressing the correlation between soil management, soil biodiversity, and human well-being. Human well-being outcomes are either unidentified or vaguely defined, lacking benchmarks and provisions for assessment.

In this regard, it must be considered that human well-being may have different priorities at the global and local scales. Additionally, there is a lack of human resources and budget allocation for the design and monitoring of indicators within the Sustainable Development Goals (SDGs). Surveys and monitoring activities should be developed at the appropriate scale of interest, with economic and human resources allocated for their implementation. Additionally, institutional frameworks should be established to ensure their stability in the face of governmental changes.

A straightforward monitoring instrument tailored to collect data for assessing measures and their consequences would be positive to integrate the dimension of human well-being into decisions and advice related to soil management, as well as to support research activities. SMART human well-being outcomes and benchmarks, relevant to the identified societal challenges and national/local context, should be identified and are assessed at regularly occurring intervals.

5.2. Beneficiaries

5.2.1. The stakeholders and beneficiaries have been identified and governance processes are participatory, inclusive, transparent and empowering

Extensive stakeholder analyses have not been conducted and even if some of the main stakeholders have been identified, not all direct and indirect stakeholders are involved, and they are not adequately

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

informed about all processes related to farming. There is a lack of collaboration structures and links between farmers and government institutions for consultations or any other participatory process.

In this regard, regional stakeholder analysis and mapping could be useful as a first step to create instruments and cooperation agreements that allow more participative governance among farmers and include all stakeholders in a comprehensive assessment across different agriculture types. A multi-scale multi-sector stakeholder analysis would help to identify who may be directly and indirectly affected by the intervention. Decision-making processes should take into account the rights and interests of all participating and affected stakeholders, with specific attention paid to stakeholders subject to extreme inequity. The procedures should be documented and this documentation should be transparent and accessible. Feedback and grievance resolution mechanism should be developed in full consultation with affected stakeholders at the appropriate scale. It is crucial to establish cooperation agreements to create dissemination and transfer channels for the various groups involved in agricultural production. The most effective approach would be to establish agricultural use and management policies at the regional level, involving farmers, NGO representatives, and government officials.

5.2.2. The rights, usage of and access to land and resources, along with the responsibilities of different stakeholders are acknowledged and respected

One of the primary barriers to achieving a higher score in this criterion is the lack of funding and human resources to define and conduct a comprehensive stakeholder mapping analysis. While rights, usage, and access to land and resources, as well as stakeholder responsibilities, are generally identified, they are not formally incorporated into an analysis. There is a need for instruments to facilitate access to land for peasant families interested in pursuing organic or agroecological productions. The rights, usage of and access to land and resources, as well as stakeholder responsibilities should be also analysed using a stakeholder mapping/analysis and respected.

5.2.3. SSM practices are economically feasibility

Little economic information has emerged about soil protection and sustainable land management practices for croplands and there is no comprehensive economic appraisal to effectively help guide investment decisions (Tepes et al., 2021). Human and economical resources should be dedicated to develop economical analysis that ensure the feasibility of the SSM practices and assess gross and net costs considering national subsidies.

The main direct and indirect costs and benefits should have been analysed, verified, and thoroughly documented. The analysis should encompass costs and benefits related to trade-offs, both at the SSM site and the larger landscape/seascape, throughout the intervention time-scale. The distribution of costs and benefits should be well understood, and a comprehensive cost-effectiveness study should have been conducted. Long-term economic and financial sustainability, as well as economic risks, should be thoroughly understood. The effectiveness and affordability of the intervention against the next best alternatives should be fully justified, understood, and documented. A comprehensive review of resourcing options should have been undertaken, and a complete resourcing package assembled and negotiated, including provision for future revenue streams.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

During the evaluation developed in T6.1.1, several barriers related to the economic feasibility of the SSM were identified. These barriers primarily stem from a lack of a comprehensive and verified understanding of the overall distribution of major costs and benefits, particularly indirect ones that are often recognized but not quantified. The challenge of precisely assessing the costs and benefits of soil protection has led some authors to the conclusion that adaptation costs are ultimately influenced by the goals set by authorities and institutions (Kuhlman et al., 2010). No evidence was found regarding a formal analysis of costs and benefits in the field. However, farmers do receive subsidies and support to farm organically because it is well-acknowledged that yields are typically not as high in organic production, but the benefits to the environment are worthwhile and therefore incentivised by policies.

A more thorough analysis and documentation of the long-term costs and benefits associated with organic soil management practices are essential. This should include a comprehensive examination of their environmental impact and broader societal implications, including consumers, especially regarding food nutrition.

Tepes et al., 2021 shows that most soil protection and sustainable land management practices may not pass the cost/benefit test and that their benefits are not, as is often assumed, systematically higher than their costs, and therefore, considering such practices as “no-regret” may have considerable unintended negative consequences. Practices to protect soil can have opposite outcomes depending on context variables such as the location and current state of the system where the practice is implemented (Tepes et al., 2021).

Considering that the rankings of alternative solutions are very sensitive to the decision-maker priorities, multidisciplinary and participative approaches in the economics of soil protection, beyond cost-benefit data and pure monetary aspects, may reduce such estimation biases and improve, upscale and incentivize soil protection measures and sustainable land management guidance (Tepes et al., 2021). Future research could examine the identification of site-specific drivers influencing the costs and benefits of these measures, as well as the linkage between economic drivers and other socioeconomic factors crucial in farmers' decision-making.

5.3. Responses

5.3.1. Lessons learned are documented and shared

While there are various experiences related to communication strategies, often associated with commercial activities, advisory services, and science and research dissemination, other knowledge-sharing experiences may be lacking systematization, specificity or accessibility. There is not a clear detailed strategy about how these communications will change behaviours and trigger transformational change. In this regard, the continuous communication between research, consultants, advisors, and farmers on findings from trials can be a slow process and therefore is not always up to date.

Initiatives to facilitate peer-to-peer learning, as well as government and commercial activities to support knowledge transfer within organic farming should be reinforced, and oriented to develop adapted to each context and market conditions.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

More practical advice should be shared with farmers on how to improve soil health and biodiversity, including the newest findings and the relevant production trade-offs. Furthermore, there is a need to establish spaces for cooperation between farmers and research directly on the farms themselves.

Lessons learned should be systematically captured and shared in an accessible manner and the communication strategy should identify how changes in behaviour trigger transformational change.

5.3.2. SSM practices are managed adaptively, based on iterative learning

In many cases, a formal long-term learning framework is lacking. Informal methods, such as field workshops, events, advisory and training services, as well as peer-to-peer learning facilitated by open days, farmer discussion groups, and networks, could be strengthened. It is important to organize stakeholder meetings with active participation from organic farmers. Additionally, there is a need for more frequent monitoring, larger scale assessments, and the development of dissemination plans to operationalize the SBWF.

A learning framework should be applied throughout the intervention lifecycle and continuously utilized to learn and adapt in response to the results of the monitoring and evaluation plan. Adaptive management and learning processes should be documented, including the definition of responses to react if deviations from the strategy occur.

5.3.3. A monitoring and evaluation plan is implemented to assess unintended adverse consequences on nature and review the established safeguards.

Existing monitoring and evaluation plans should be strengthened with additional funding and human resources to establish incentives for regular implementation and build a systematic framework that address coordination challenges associated with conducting large-scale research. This criterion is not highly achieved, primarily due to fragmented administrative structures related to ecological issues and lack of resources specifically oriented for monitoring and evaluation.

In relation to croplands, various parameters are monitored as part of the efforts to oversee farming practices labelled as 'organic.' Nevertheless, government controls are frequently perceived as unfair, for not taking into account the financial implications for farmers, especially those focused on preventing nitrate leaching. The allocation of specific funding for monitoring and evaluation activities, coupled with the simplicity and user-friendliness of these activities, could facilitate their feasibility and promotion.

Additionally, collecting data to establish a baseline is crucial in developing monitoring and evaluation plans. The baseline serves as a reference point against which changes over time can be compared, enabling the assessment of intervention effectiveness and the detection of unforeseen negative impacts on nature. Furthermore, setting specific thresholds for each indicator or metric is essential for quickly identifying deviations from established goals, allowing for timely preventive measures to avoid irreversible harm to the ecosystem.

Guerra et al., 2021 suggest that soil monitoring will not be feasible without a broad network of local partners covering various ecosystems and environmental conditions. This includes the establishment

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

of a centralized global analysis network involving different volunteering institutions, enabling a high level of standardization and analytical power.

To better align SSM practices with this criterion, a strategy should be in place that states intended outcomes, actions, and assumptions made in regards to economic, social, and ecological conditions. The strategy should elaborate on how assumptions may change and should be consistently used as a basis for monitoring and evaluation of the intervention. Possible adverse impacts of SSM interventions on ecosystems, ecological processes, and species should be identified. A monitoring and evaluation system of potential adverse impacts should be properly implemented. Safeguards should be periodically reviewed with clear documentation of this being provided.

The Proposal for a Directive on Soil Monitoring and Resilience establish a monitoring framework by Member States, based on common soil descriptors and criteria. Generally, the monitoring framework should be able to reflect progress towards achieving soil health in order to incentivise practitioners. Unfortunately, the proposed one-out- all-out principle – only considering a soil healthy when it meets all criteria listed in Annex I - would not allow to show progress. Instead, tracking improvements in trends in soil health would allow to understand progress towards achieving healthy soils, and identify in which areas efforts are most needed.

Promoting sustainable soil management practices is key in order to achieve healthy soils. Therefore, it would be desirable to include binding targets on soil management. Those binding targets could be inspired by the principles established on sustainable soil management. Characteristics of SSM defined by FAO, 2017 (see Appendix A) would be also useful as a base to define binding targets.

Soil sampling protocols must be adapted to the local soil types, e.g., natural soils have often variable layers as they are not homogenized by human activities as cultivated soils. For example, the suggested LUCAS sampling design is not optimal for soils in forests and peatlands. Furthermore, often deeper sampling is needed to obtain correct understanding of soil C stocks. Future soil monitoring efforts should be better connected to existing aboveground monitoring as land use and productivity determine greatly soil characteristics, and this is also the only way to understand causal relationships. Thus, the forthcoming monitoring should utilize the previous (EU-level or national) monitoring data series (as ICP Forest). In the case of LUCAS, more detailed aboveground descriptions should be included into the monitoring to increase the utility of the soil data. Given the time scale of soils, it might be more suitable to concentrate monitoring efforts in a longer sampling history, and to prioritise obtaining good quality aboveground data rather than high quantity of samples.

The Land health monitoring framework described by Dussán López, (2023), could serve as a useful guideline to enhance a better alignment of several SSM with monitoring. It includes three groups of indicators for assessing biodiversity in croplands: belowground, aboveground and habitat diversity, which, taken together, are representative of the field (soil), farm and land- scape levels, as well as the three levels of agrobiodiversity: genetic, species and ecosystem.

According to Guerra et al., 2021, monitoring programs should include a strong commitment to capacity-building and knowledge-sharing mechanisms, as well as an open access archive of soil biodiversity resources.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

5.3.4. Relevant policies, regulation frameworks and national and global targets are identified and considered in the SSM practices design

SSM practices should incorporate a review of policies, regulations, and laws that are relevant to the SSM, and these can be used to support their uptake and mainstreaming. Relevant national and global targets for human well-being, climate change, and biodiversity should be identified. An analysis of policies and targets related to the implementation of SSM should also be developed to facilitate their consideration in management. These aspects will be further developed in T6.2 and D6.3.

5.3.5. SSM practices inform and enhance facilitating policy and regulation frameworks and contribute to national and global targets

Where necessary and possible, the SSM regimes should inform and enhance policy frameworks amendment. Relevant national and global targets for human well-being, climate change, and biodiversity should be identified and the potential contribution of the SSM to these targets should be identified and reported in the relevant platforms. There is also a lack of institutional cooperation with citizens, local administrative organizations, and rural stakeholders. The inclusion of cooperation indicators and frameworks in the public policy agendas of these stakeholders is necessary. These aspects will be further developed in T6.2 and D6.3.

6. References

Antoine, C. M., & Forrest, J. R. K. (2021). Nesting habitat of ground-nesting bees: A review. *Ecological Entomology*, *46*(2), 143-159. https://doi.org/10.1111/een.12986

Bengtsson, J., Ahnström, J., & Weibull, A.-C. (2005). The effects of organic agriculture on biodiversity and abundance: A meta-analysis: Organic agriculture, biodiversity and abundance. *Journal of Applied Ecology*, *42*(2), 261-269. https://doi.org/10.1111/j.1365-2664.2005.01005.x

Bhandari, K. B., West, C. P., Acosta-Martinez, V., Cotton, J., & Cano, A. (2018). Soil health indicators as affected by diverse forage species and mixtures in semi-arid pastures. *Applied Soil Ecology*, *132*, 179-186. https://doi.org/10.1016/j.apsoil.2018.09.002

Briones, M. J. I., & Schmidt, O. (2017). Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. *Global Change Biology*, *23*(10), 4396-4419. https://doi.org/10.1111/gcb.13744

Brussaard, L., De Ruiter, P. C., & Brown, G. G. (2007). Soil biodiversity for agricultural sustainability. *Agriculture, Ecosystems & Environment*, *121*(3), 233-244. https://doi.org/10.1016/j.agee.2006.12.013

Byrnes, R. C., Eastburn, D. J., Tate, K. W., & Roche, L. M. (2018). A Global Meta-Analysis of Grazing Impacts on Soil Health Indicators. *Journal of Environmental Quality*, *47*(4), 758-765. https://doi.org/10.2134/jeq2017.08.0313

Chen, J., Chazdon, R. L., Swenson, N. G., Xu, H., & Luo, T. (2021). Drivers of soil microbial community assembly during recovery from selective logging and clear-cutting. *Journal of Applied Ecology*, *58*(10), 2231-2242. https://doi.org/10.1111/1365-2664.13976

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Cohen-Shacham, E., Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C., Maginnis, S., Maynard, S., Nelson, C. R., Renaud, F. G., Welling, R., & Walters, G. (2019). Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science & Policy*, *98*, 20-29. https://doi.org/10.1016/j.envsci.2019.04.014

Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, *15*(1), 3-11. https://doi.org/10.1016/S0929-1393(00)00067-6

Dussán López, P. (2023). *Land health monitoring framework: Towards a tool for assessing functional and habitat diversity in agroecosystems* (J. Davies, L. Larbodière, M. Muñoz Cañas, & J. Dalton, Eds.). IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/LCRH6058

Edwards, D. P., & Laurance, W. F. (2013). Biodiversity Despite Selective Logging. *Science*, *339*(6120), 646-647. https://doi.org/10.1126/science.339.6120.646-b

Eisenhauer, N., Dobies, T., Cesarz, S., Hobbie, S. E., Meyer, R. J., Worm, K., & Reich, P. B. (2013). Plant diversity effects on soil food webs are stronger than those of elevated CO_2 and N deposition in a long-term grassland experiment. *Proceedings of the National Academy of Sciences*, *110*(17), 6889-6894. https://doi.org/10.1073/pnas.1217382110

European Commission. (2023a). *Annexes to the proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law)*.

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

European Commission. (2023c, enero 27). *Nature-based solutions*. https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions_en

European Court of Auditors. (2019). *Biodiversity in farming*. Retrieved from https://www.eca.europa.eu/Lists/ECADocuments/AP19_09/AP_BIODIVERSITY_EN.pdf

Eurostat. (2021). *Land use statistics*. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Land_use_statistics#:~:text=Agricultural%20land%20use%20is%20the,2018%20(see%20Figure%201).

FAO. (2017). *Voluntary Guidelines for Sustainable Soil Management*. Food and Agriculture Organization of the United Nations Rome, Italy,. https://www.fao.org/3/i6874en/I6874EN.pdf

FAO, ITPS, GSBI, CBD, & EC. (2020). *State of knowledge of soil biodiversity—Status, challenges and potentialities*. FAO. https://doi.org/10.4060/cb1928en

França, F. M., Frazão, F. S., Korasaki, V., Louzada, J., & Barlow, J. (2017). Identifying thresholds of logging intensity on dung beetle communities to improve the sustainable management of Amazonian tropical forests. *Biological Conservation*, *216*, 115-122. https://doi.org/10.1016/j.biocon.2017.10.014

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Gao, T., Nielsen, A. B., & Hedblom, M. (2015). Reviewing the strength of evidence of biodiversity indicators for forest ecosystems in Europe. *Ecological Indicators*, *57*, 420-434. https://doi.org/10.1016/j.ecolind.2015.05.028

Garland, G., Edlinger, A., Banerjee, S., Degrune, F., García-Palacios, P., Pescador, D. S., Herzog, C., Romdhane, S., Saghai, A., Spor, A., Wagg, C., Hallin, S., Maestre, F. T., Philippot, L., Rillig, M. C., & Van Der Heijden, M. G. A. (2021). Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. *Nature Food*, *2*(1), 28-37. https://doi.org/10.1038/s43016-020-00210-8

Ghimire, R., Norton, J. B., Stahl, P. D., & Norton, U. (2014). Soil Microbial Substrate Properties and Microbial Community Responses under Irrigated Organic and Reduced-Tillage Crop and Forage Production Systems. *PLoS ONE*, *9*(8), e103901. https://doi.org/10.1371/journal.pone.0103901

Gibson, L., Lee, T. M., Koh, L. P., Brook, B. W., Gardner, T. A., Barlow, J., Peres, C. A., Bradshaw, C. J. A., Laurance, W. F., Lovejoy, T. E., & Sodhi, N. S. (2011). Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, *478*(7369), 378-381. https://doi.org/10.1038/nature10425

Guerra, C. A., Bardgett, R. D., Caon, L., Crowther, T. W., Delgado-Baquerizo, M., Montanarella, L., Navarro, L. M., Orgiazzi, A., Singh, B. K., Tedersoo, L., Vargas-Rojas, R., Briones, M. J. I., Buscot, F., Cameron, E. K., Cesarz, S., Chatzinotas, A., Cowan, D. A., Djukic, I., Van Den Hoogen, J., … Eisenhauer, N. (2021). Tracking, targeting, and conserving soil biodiversity. *Science*, *371*(6526), 239-241. https://doi.org/10.1126/science.abd7926

Hawes, C., Alexander, C. J., Begg, G. S., Iannetta, P. P. M., Karley, A. J., Squire, G. R., & Young, M. (2018). Plant Responses to an Integrated Cropping System Designed to Maintain Yield Whilst Enhancing Soil Properties and Biodiversity. *Agronomy*, *8*(10), 229. https://doi.org/10.3390/agronomy8100229

Heinen, J., Smith, M. E., Taylor, A., & Bommarco, R. (2023). Combining organic fertilisation and perennial crops in the rotation enhances arthropod communities. *Agriculture, Ecosystems & Environment*, *349*, 108461. https://doi.org/10.1016/j.agee.2023.108461

Heinonen, T., Pukkala, T., Mehtätalo, L., Asikainen, A., Kangas, J., & Peltola, H. (2017). Scenario analyses for the effects of harvesting intensity on development of forest resources, timber supply, carbon balance and biodiversity of Finnish forestry. *Forest Policy and Economics*, *80*, 80-98. https://doi.org/10.1016/j.forpol.2017.03.011

Ikoyi, I., Grange, G., Finn, J. A., & Brennan, F. P. (2023). Plant diversity enhanced nematode-based soil quality indices and changed soil nematode community structure in intensively-managed agricultural grasslands. *European Journal of Soil Biology*, *118*, 103542. https://doi.org/10.1016/j.ejsobi.2023.103542

IUCN. (2020). *Global Standard for Nature-based Solutions: A user-friendly framework for the verification, design and scaling up of NbS: first edition*. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.08.en

Jones, A., Panagos, P., Barcelo, S., Bouraoui, F., Bosco, C., Dewitte, O., Gardi, C., Erhard, M., Hervas, D. D. F., Hiederer, R., Jeffery, S., Lükewille, A., Marmo, L., Montanarella, L., Olazabal, C., Petersen, J.-E.,

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Penizek, V., Strassburger, T., Toth, G., … Yigini, Y. (2013, marzo 11). *The State of Soil in Europe: A contribution of the JRC to the European Environment Agency's Environment State and Outlook Report—SOER 2010*. JRC Publications Repository. https://doi.org/10.2788/75626

Kendzior, J., Warren Raffa, D., & Bogdanski, A. (2022). *The soil microbiome: A game changer for food and agriculture*. FAO. https://doi.org/10.4060/cc0717en

Kuhlman, T., Reinhard, S., & Gaaff, A. (2010). Estimating the costs and benefits of soil conservation in Europe. *Land Use Policy*, *27*(1), 22-32. https://doi.org/10.1016/j.landusepol.2008.08.002

Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., Mellado-Vázquez, P. G., Malik, A. A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B. C., Trumbore, S. E., & Gleixner, G. (2015). Plant diversity increases soil microbial activity and soil carbon storage. *Nature Communications*, *6*(1), 6707. https://doi.org/10.1038/ncomms7707

Larbodière, L., Davies, J., Schmidt, R., Magero, C., Vidal, A., Arroyo Schnell, A., Bucher, P., Maginnis, S., Cox, N., Hasinger, O., Abhilash, P. C., Conner, N., Westerburg, V., & Costa, L. (2020). *Common ground: Restoring land health for sustainable agriculture*. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.10.en

Legrand, F., Picot, A., Cobo-Díaz, J. F., Carof, M., Chen, W., & Le Floch, G. (2018). Effect of tillage and static abiotic soil properties on microbial diversity. *Applied Soil Ecology*, *132*, 135-145. https://doi.org/10.1016/j.apsoil.2018.08.016

Li, Y., Zhang, Q., Cai, Y., Yang, Q., & Chang, S. X. (2020). Minimum tillage and residue retention increase soil microbial population size and diversity: Implications for conservation tillage. *Science of The Total Environment*, *716*, 137164. https://doi.org/10.1016/j.scitotenv.2020.137164

Loranger-Merciris, G., Barthes, L., Gastine, A., & Leadley, P. (2006). Rapid effects of plant species diversity and identity on soil microbial communities in experimental grassland ecosystems. *Soil Biology and Biochemistry*, *38*(8), 2336-2343. https://doi.org/10.1016/j.soilbio.2006.02.009

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., & Gattinger, A. (2017). Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. *PLOS ONE*, *12*(7), e0180442. https://doi.org/10.1371/journal.pone.0180442

Lynch, D. H. (2022). Soil Health and Biodiversity Is Driven by Intensity of Organic Farming in Canada. *Frontiers in Sustainable Food Systems*, *6*, 826486. https://doi.org/10.3389/fsufs.2022.826486

Mann, C., Lynch, D., Fillmore, S., & Mills, A. (2019). Relationships between field management, soil health, and microbial community composition. *Applied Soil Ecology*, *144*, 12-21. https://doi.org/10.1016/j.apsoil.2019.06.012

Mathew, R. P., Feng, Y., Githinji, L., Ankumah, R., & Balkcom, K. S. (2012). Impact of No-Tillage and Conventional Tillage Systems on Soil Microbial Communities. *Applied and Environmental Soil Science*, *2012*, 1-10. https://doi.org/10.1155/2012/548620

Niemela, J. (1997). Invertebrates and Boreal Forest Management. Invertebrados y Manejo de Bosques Boreales. *Conservation Biology*, *11*(3), 601-610. https://doi.org/10.1046/j.1523-1739.1997.06008.x

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Oberč, B. P., & Arroyo Schnell, A. (2020). *Approaches to sustainable agriculture: Exploring the pathways towards the future of farming*. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.07.en

Orgiazzi, A. (2022). What is soil biodiversity? *Conservation Letters*, *15*(1), e12845. https://doi.org/10.1111/conl.12845

Orgiazzi, A., Bardgett, R.D., Barrios, E., Behan-Pelletier, V., Briones, M.J.I., Chotte, J-L., De Deyn, G.B., Eggleton, P., Fierer, N., Fraser, T., Hedlund, K., Jeffery, S., Johnson, N.C., Jones, A., Kandeler, E., Kaneko, N., Lavelle, P., Lemanceau, P., Miko, L., … Wall, D.H. (2016). *Global soil biodiversity atlas.* European Commission, Publications Office of the European Union. https://data.europa.eu/doi/10.2788/2613

Peura, M., Burgas, D., Eyvindson, K., Repo, A., & Mönkkönen, M. (2018). Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. *Biological Conservation*, *217*, 104-112. https://doi.org/10.1016/j.biocon.2017.10.018

Plantureux, S., Peeters, A., & McCracken, D. (2005). Biodiversity in intensive grasslands: Effect of management, improvement and challenges. *Agronomy Research*, *3*, 153-164.

Reed, K., & Morrissey, E. M. (2022). Bridging Ecology and Agronomy to Foster Diverse Pastures and Healthy Soils. *Agronomy*, *12*(8), 1893. https://doi.org/10.3390/agronomy12081893

Roarty, S., & Schmidt, O. (2013). Permanent and new arable field margins support large earthworm communities but do not increase in-field populations. *Agriculture, Ecosystems & Environment*, *170*, 45-55. https://doi.org/10.1016/j.agee.2013.02.011

Ryan, K. B., De Menezes, A., Finn, J. A., & Brennan, F. P. (2023). Plant species and soil depth differentially affect microbial diversity and function in grasslands. *Journal of Sustainable Agriculture and Environment*, sae2.12077. https://doi.org/10.1002/sae2.12077

Shackelford, G. E., Kelsey, R., & Dicks, L. V. (2019). Effects of cover crops on multiple ecosystem services: Ten meta-analyses of data from arable farmland in California and the Mediterranean. *Land Use Policy*, *88*, 104204. https://doi.org/10.1016/j.landusepol.2019.104204

Simard, S. W., Roach, W. J., Beauregard, J., Burkart, J., Cook, D., Law, D., Murphy-Steed, A., Schacter, T., Zickmantel, A., Armstrong, G., Fraser, K. M., Hart, L., Heath, O. R. J., Jones, L., Sachs, N. S., Sachs, H. R., Snyder, E. N., Tien, M., & Timmermans, J. (2021). Partial Retention of Legacy Trees Protect Mycorrhizal Inoculum Potential, Biodiversity, and Soil Resources While Promoting Natural Regeneration of Interior Douglas-Fir. *Frontiers in Forests and Global Change*, *3*, 620436. https://doi.org/10.3389/ffgc.2020.620436

Tepes, A., Galarraga, I., Markandya, A., & Sánchez, M. J. S. (2021). Costs and benefits of soil protection and sustainable land management practices in selected European countries: Towards multidisciplinary insights. *Science of The Total Environment*, *756*, 143925. https://doi.org/10.1016/j.scitotenv.2020.143925

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

Timmerman, A., Bos, D., Ouwehand, J., & De Goede, R. G. M. (2006). Long-term effects of fertilisation regime on earthworm abundance in a semi-natural grassland area. *Pedobiologia*, *50*(5), 427-432. https://doi.org/10.1016/j.pedobi.2006.08.005

Triviño, M., Pohjanmies, T., Mazziotta, A., Juutinen, A., Podkopaev, D., Le Tortorec, E., & Mönkkönen, M. (2017). Optimizing management to enhance multifunctionality in a boreal forest landscape. *Journal of Applied Ecology*, *54*(1), 61-70. https://doi.org/10.1111/1365-2664.12790

UNEA. (2022). *Draft resolution on nature-based solutions for supporting sustainable development.* United Nations Environment Assembly of the United Nations Environment Programme, Fifth session., Nairobi i.

Xu, H., Li, Y., Liu, S., Zang, R., He, F., & Spence, J. R. (2015). Partial recovery of a tropical rain forest a half-century after clear-cut and selective logging. *Journal of Applied Ecology*, *52*(4), 1044-1052. https://doi.org/10.1111/1365-2664.12448

Yang, G., Wagg, C., Veresoglou, S. D., Hempel, S., & Rillig, M. C. (2018). How Soil Biota Drive Ecosystem Stability. *Trends in Plant Science*, *23*(12), 1057-1067. https://doi.org/10.1016/j.tplants.2018.09.007

Yousefi, M., Dray, A., & Ghazoul, J. (2024). Assessing the effectiveness of cover crops on ecosystem services: A review of the benefits, challenges, and trade-offs. *International Journal of Agricultural Sustainability*, *22*(1), 2335106. https://doi.org/10.1080/14735903.2024.2335106

Zak, D. R., Holmes, W. E., White, D. C., Peacock, A. D., & Tilman, D. (2003). PLANT DIVERSITY, SOIL MICROBIAL COMMUNITIES, AND ECOSYSTEM FUNCTION: ARE THERE ANY LINKS? *Ecology*, *84*(8), 2042-2050. https://doi.org/10.1890/02-0433

Zhao, J., Wan, S., Fu, S., Wang, X., Wang, M., Liang, C., Chen, Y., & Zhu, X. (2013). Effects of understory removal and nitrogen fertilization on soil microbial communities in Eucalyptus plantations. *Forest Ecology and Management*, *310*, 80-86. https://doi.org/10.1016/j.foreco.2013.08.013

Zhao, J., Wang, X., Wang, X., & Fu, S. (2014). Legume-soil interactions: Legume addition enhances the complexity of the soil food web. *Plant and Soil*, *385*(1-2), 273-286. https://doi.org/10.1007/s11104-014-2234-2

Zhao, J., Zeng, Z., He, X., Chen, H., & Wang, K. (2015). Effects of monoculture and mixed culture of grass and legume forage species on soil microbial community structure under different levels of nitrogen fertilization. *European Journal of Soil Biology*, *68*, 61-68. https://doi.org/10.1016/j.ejsobi.2015.03.008

7. Appendix A. Sustainable Soil Management characteristics

According to FAO, 2017, SSM are associated to the following characteristics:

1. Minimal rates of soil erosion by water and wind;
2. The soil structure is not degraded and provides a stable physical context for movement of air, water, and heat, as well as root growth;
3. Sufficient surface cover is present to protect the soil;

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.

4. The store of soil organic matter is stable or increasing and ideally close to the optimal level for the local environment;
5. Availability and flows of nutrients are appropriate to maintain or improve soil fertility and productivity, and to reduce their losses to the environment;
6. Soil salinization, sodification and alkalinization are minimal;
7. Water is efficiently infiltrated and stored to meet the requirements of plants and ensure the drainage of any excess;
8. Contaminants are below toxic levels;
9. Soil biodiversity provides a full range of biological functions;
10. The soil management systems for producing food, feed, fuel, timber, and fibre rely on optimized and safe use of inputs; and
11. Soil sealing is minimized through responsible land use planning.

The research leading to these results has received funding from the European Union Horizon 2020 Research & Innovation programme under the Grant Agreement no. 101000371.