Forest soil management practices, modelling and monitoring to mitigate climate change and enhance ecosystem services

A synthesis of HoliSoils project results for

Policymakers

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HoliSoils

Working together for forest soils

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Introduction

Forest soils are complex systems comprising many component parts: minerals, organic matter, air, water, and a diverse array of organisms. They facilitate complex processes such as nutrient cycling, organic matter decomposition, and water filtration, which are essential for plant growth and ecosystem functioning. To people, too, these functions provide ecosystem services. Among them are biomaterials provision, water purification, erosion control, habitat for biodiversity, and carbon sequestration and storage.

However, approximately one third of the world's soils are degraded, jeopardising not only agricultural productivity and food security as well as general ecosystem health, but also other ecosystem services they provide no insignificant part of which are provided by forest soils. Some 60 - 70% of all soils In the EU are classified as 'unhealthy' and the loss of the organic carbon stored in them, alongside erosion and biodiversity decline, are among the main reasons for this classification. This means that improving and maintaining soil health is of paramount importance today.

The **HoliSoils** project (Horizon 2020, May 2021 – October 2025) identified and tested forest soil management practices aiming to mitigate climate change and sustain provision of ecosystem services, as well as furthering novel methodologies and expert knowledge on analytical techniques, data sharing, soil properties,

biodiversity, and model development. Its results, presented initially as a project deliverable D7.4 Synthesis of HoliSoils' results and now in this document, promote an advanced understanding of soil properties and dynamics, offer collections of and facilitate access to data about soil vulnerability and recovery potential, propose harmonising soil monitoring across Europe, and share guidance on good management practice to optimise forest soil health. Importantly, the project has produced a number of hands-on tools that can be used by various stakeholders such as policy makers, practitioners, sector representatives, experts, learners and teachers in relevant disciplines, and lay audiences.

While the original report included six discrete subsections, each targeting a specific audience important for HoliSoils—namely policy makers, practitioners, sector, expert, education, and general—the report is now divided into separate publications according to these audiences.

This edition of the report is intended for policy makers at all levels: local, regional, national, and supranational. It is for elected representatives in governments and parliaments, for civil servants in administration and institutions, for political advisers, and for NGOs.

Selected key messages

- **Forest soils provide crucial services to people – from timber production to carbon sequestration and storage to mitigate climate change.** Soils across European forest ecosystems contain vast amounts of carbon, but they are regionally vulnerable to carbon loss. Forest management practices can be optimised to prevent carbon loss and enhance uptake.

- **Forest management practices and forest use impact soil health in different ways.** Climate - Smart Forestry (CSF) practices and sustainable post-disturbance recovery activities are beneficial for soil health, including biodiversity and carbon retention, as well as long-term productivity.

- **Forest soils are complex systems consisting of biotic and abiotic components engaged in physical, chemical, and biological processes.** Improved conceptual and simulation models have been developed that help to further understanding of soil functioning, vulnerability, recovery potential and to inform management decisions that promote and preserve soil health.

- **Soils have been degraded and are vulnerable to degradation across Europe and the world. The EU Soil Monitoring Law aims to improve, maintain, and safeguard soil health.** Harmonised sampling and assessment methodologies are now available that help capture the particular considerations relevant to forest soils to ensure consistent reporting, balanced funding allocation and effective remedial action for the health of all soils across the EU.

A multitude of communication and dissemination materials for various audiences have been produced as a result of the HoliSoils project. These can be found in the HoliSoils web portal, Resources section of the project website and Project CORDIS page.

Full information about the project can be found on the
https://holisoils.eu

Report outline

This report consists of two parts

Part 1 provides information about the project itself, its aims and methods as well its contributions and key findings. It first summarises the HoliSoils project's background and objectives. Then it provides information about the experimental work and test sites that form the empirical foundation of the project, which were used to study soil properties and dynamics, and responses to different forest management and post-disturbance recovery treatments. Finally, this part of the report concludes by outlining the project's contributions to the understanding of forest soils, and how to monitor and manage them. It also highlights the key messages resulting from the in-depth analysis of soil characteristics, processes, and responses to different treatments.

Part 2 of the report presents project results for policy makers such as materials and tools that are based on this research and can be put to practical use.

The project deliverable **D7.4 Synthesis of HoliSoils' results** included six discrete sub-sections, each targeting a specific audience:

- **Policy audience:** local / regional / national governments and administrations, parliamentarians, political advisers, supranational institutions, NGOs.
- **Practitioner audience:** forest and landowners, practitioners in forest management, environmental protection organisations.
- **Sector audience:** forest-related public and private sector organisations, representatives from forestry and bio-based value chains (incl. carbon markets), investors in the field, certification bodies, innovation acceleration endeavours.
- **Expert audience:** greenhouse gas inventory experts on land use, soil monitoring experts, researchers.
- **Education audience:** university and vocational training, forest pedagogues, instructors, students, forest extension services.
- **General audience:** general public, media, interested and informed citizens, young people, community groups, interested and informed citizens, campaigners, etc.

For public dissemination purposes, the report is now divided into separate publications according to the audiences above. Readers are therefore advised to consult the version of the report dedicated to them to put the project's recommendations into practice in the most impactful way.

Note: This report synthesises HoliSoils findings available at the time of writing and stemming from a co-creation exercise, carried out in April 2025, to identify project outputs for end users and key overarching messages, which involved partners in the project consortium and members of the HoliSoils Stakeholder and End-user Advisory Board. Major findings produced subsequently will be included in the targeted dissemination materials, which will be available for download via links provided from the HoliSoils website and the HoliSoils web portal.

Part 1

1. Project background and objectives

HoliSoils – 'Holistic management practices, modelling and monitoring for European forest soils' – is a 4.5-year project funded by the European Commission from May 2021 – October 2025.
A consortium of twenty international partners covering many European countries but also involving global partners from Uruguay and Japan carried out research activities to improve scientific understanding of the components and dynamics of forest soils, and developed a set of publicly available information and tools for practical application in preserving soil health.

1.1 Project background and summary

Knowledge gaps on forest soil processes and lack of a harmonised soil monitoring limit the EU's ability to maintain soil related ecosystem services and to reach climate policy targets. A better understanding of the soil components, processes, functions and regional specificities and vulnerability, management and integration of data into computational models that can be used for decision making, and a shared methodology for assessing soil parameters and health are urgently required in order to meet climate and sustainability goals, including the UN's Agenda 2030 SDGs, the Paris Agreement of Climate Convention, the EU Bioeconomy Strategy, the EU's Land Use, Land Use Change and Forestry (LULUCF) Regulation, the EU Forest Strategy (2018), the EU Biodiversity Strategy for 2030, the EU's Nature Restoration Regulation (2024), and the European Green Deal.

In response to these challenges, HoliSoils:

- **Tested the suitability of soil management practices** to mitigate climate change and disturbance impacts as well as sustain provision of ecosystem services essential for human livelihoods and wellbeing across different forest ecosystems and conditions.
- **Developed, contributed to and improved methodologies, models, databases and tools** currently in use and for future use in decision making in forestry management practice and soil health, as well as greenhouse gas (GHG) assessment.
- **Proposed a harmonised forest soil monitoring and assessment framework.**

HoliSoils applied a collaborative multi-actor approach to maximise the project's applicability and impact beyond its duration. The multidisciplinary consortium consisted of universities and research institutes from across Europe, with leading expertise on soil analysis and databases, development of advanced analytical techniques,

complex system modelling, digital soil mapping, soil ecology, disturbance ecology, forest and GHG inventories, social sciences, and communications. It also involved active engagement of diverse stakeholders, including forest owners and managers, actors in the forest industry and wood supply chain, forest extension services, certification bodies, forest and soil researchers, climate policy support and GHG inventory experts, and policymakers.

1.2 Project objectives

To address the challenges outlined above, HoliSoils set itself a number of discrete objectives – each contributing beneficial practical impacts to optimising the maintenance and utility of European forest soils.

- **Advance knowledge of soil properties, processes, biodiversity and soil microbiota activity,** all of which influence soil-based ecosystem services such as wood production, reduction of greenhouse gas emissions, water supply, soil nutrient retention, avoidance of land degradation.
- **Develop and improve state-of-the-art soil models and harmonise them into a monitoring framework** for estimating carbon and greenhouse gas fluxes, nitrogen and base cation stocks in forest soils, and integrate them into forest ecosystem models.
- **Determine the effects of management on soil functioning** taking into account biodiversity, nutrient stocks, organic matter quality and stabilisation processes.
- **Facilitate greenhouse gas reporting** by harmonising legacy soil data from multiple sources and making them available to end users via a web portal, and to develop and apply digital soil mapping methods to promote the scaling-up of the model to European scale.

- **Determine effects of natural disturbances and management practices on soil functioning** and resilience, mapping soil vulnerability and identifying and highlighting beneficial management practices to prevent of soil degradation.
- **Enhance understanding of the impacts, trade-offs, and synergies of Climate-Smart Forestry management** scenarios for soils and forests vis-a-vis the greenhouse gas balance across Europe and water budget under future climate disturbances.
- **Boost collaboration between research institutions, governance bodies and practitioners** to facilitate the transfer of developed approaches, knowledge, and tools globally to analysts, decision makers and operators within the forest sector.

2. Test Sites

2.1 Overview

Many of the findings and outputs of the HoliSoils project originate from research conducted at a number of experimental and test sites across Europe and beyond. These **sites represent key bioclimatic regions and soil types,** and were used for the mapping, modelling and harmonisation of soil data.

Field experiments were conducted in **Finland, Lithuania, Romania, Slovakia, Germany, Netherlands, France, Spain, and Uruguay.** In addition to soil type, the sites represented a broad range of environmental conditions regarding their climate classification, species composition, current management practice as well as, in

Examples of measurement and monitoring setup, Kranzberg Forest, Germany

some cases, types of disturbance they had been exposed to. They also received different experimental treatments depending on relevance and soil challenges of the region. More information about the sites can be found at: **https://holisoils.eu/test-sites/**

The experiments conducted by the HoliSoils teams were designed to **investigate the effects of soil and forest management** (including thinning regimes, tree species composition, fertilisation, rewetting, debris and deadwood management) **and natural disturbances** (forest fires, windthrow, droughts) on forest soil processes, resilience and climate change mitigation potential. Measurements of soil physico-chemical properties and biodiversity were complemented by analysis and monitoring of soil processes such as greenhouse gas fluxes and nutrient cycling.

Highlights from the findings include:

- **Conventional forestry methods are often harmful to forest soils, while locally specific Climate-Smart Forestry practices can enhance soil health.**
- **Tailored Climate-Smart Forestry practices can be used to help forest soils recover after disturbances.**
- **All forest soils across Europe are at risk of turning into carbon sources. Mediterranean soils store less carbon but are more immediately affected by non-sustainable management and disturbances (exacerbated by climatic changes), while boreal soils store more carbon and are at risk if non-sustainable management is continued under climate change conditions.**

Consortium partner & test sites countries

Test sites will be maintained by different project partners and used for further scientific study. Collaboration requests should be made to the relevant contacts (cf. tables below).

2.2 Effects of 'business as usual' forest management vs. Climate-Smart Forestry

Ctry	Location	Contact	Tree species	Soil type	Climate	Current management	Experimentation (treatment)	Results & findings
FI	Ränskälänkorpi	**Luke** Raisa Mäkipää Aleksi Lehtonen	*Picea abies, Pinus sylvestris, Betula pubescens*	Drained fen	Subarctic (Dfc)	Drained peatland forestry	Continuous cover thinning and avoided peatland ditching	Continuous cover forestry (CCF) with selection harvesting had lower net ecosystem GHG exchange than clearcutting (CC) as a result of remaining trees primary productivity. However, CCF had no effect on the soil CO2 emissions in comparison to non-harvested control. CCF had no effect on soil CH4 fluxes, whereas CC reduced soil CH4 sink and caused sources. N2O emissions were more driven by nutrient conditions but not harvesting management.
SK	Dobroc	**TUZVO** Michal Bosela Erika Gomoryova	*Fagus sylvatica, Picea abies,* *Abies alba*	Deep cambisols	Warm Summer Continental (Dfb)	Spruce monoculture as a control	Mixed stand w/ broadleaved species	Norway spruce monoculture was more drought-sensitive than silver fir and European beech mixed stand. Soil CO_2 fluxes were much lower in the spruce stand during drought. Soil CO_2 fluxes differed between stands when soil temperature exceeded 12°C. Heterotrophic respiration in spruce was more moisture-sensitive at higher temperatures. Methane oxidation dropped significantly after the 2023 clear-cut post-bark beetle event, though it recovered within a year. Microbial community analysis revealed a higher proportion of ectomycorrhizal fungi in the mixed forest, while saprotrophs dominated in the spruce stand, influencing soil carbon dynamics.
DE	Kelheim	**TUM** Fabian Weikl Karin Pritsch Thorsten Grams	*Picea abies, Fagus sylvatica*	loamy, calcareous	Warm Summer Continental (Dfb)		Mixed stands broadleaved species, experimental drought, (Kranzberg)	Soil CO_2 emissions along a precipitation gradient with low (Kelheim), medium (Kranzberg) and high (Wasserburg) precipitation were similar between sites and mostly responded to the annual and seasonal situation (2022, 2023). Averaged soil respiration on the mixed sites was higher compared with the respective pure spruce sites and likely dependent on the trees' BAI. Soil respiration did not recover three years after controlled re-watering after five years of experimental rain exclusion (Kranzberg experiment), demonstrating strong, lasting effects of recurrent droughts.
	Kranzberg			loam, loess				
	Wasserburg			loamy sand, sandy loam				

Ctry	Location	Contact	Tree species	Soil type	Climate	Current management	Experimentation (treatment)	Results & findings
NL	Ugchelen, Kroondomein, National Park Hoge Veluwe, Buunderkamp, Zwolse Bos, Weerterheide, Bergeijk, Mastbos, Dorst	**WR** Sara Filipek Mart-Jan Schelhaas Frank Sterck	*Pinus sylvestris, Pseudotsuga menziesii, Fagus sylvatica*	Poor sandy	Oceanic climate (Cfb)	Management on water-limited soils	Different thinning intensities	We investigated effects of different cutting intensities on soil respiration through its dependencies on soil microclimate, as soil temperature and moisture, in Scots pine (*Pinus sylvestris*) forests on poor sandy soils. The soil respiration monitoring was conducted on three out of five locations across the Netherlands: Kroondomein, Zwolse Bos and National Park Hoge Veluwe. Our results suggested that the high cutting intensities of clearcuts and, to a lesser extent shelterwoods, significantly amplified seasonal soil temperature changes and resulted in increased levels of soil moisture year-round. Whereas the soil respiration exhibited no significant response to the different felling intensities. Overall, our research highlighted that forests are self-regulatory and interconnected systems. In these systems, aboveground changes to canopy cover cannot be separated from belowground conditions and processes. High cutting intensities, as clearcuts, erode the resilience of forest systems, make forest soils more susceptible to extreme temperature changes, and thereby threaten the balance of soil carbon dynamics.
FR	Saint Mitre	**AMU** Mathieu Santonja Bernard Prevosto	*Pinus halepensis*	Sandy loamy calcareous	Mediterranean (Csa)			We investigated the combined influence of forest thinning and understory removal on microclimatic conditions, soil physical-chemical properties, the soil biodiversity and associated processes such as CO_2 emissions or litter decomposition efficiency. The development of a dense understory vegetation with the reduction of pine cover in the intense thinned plots led to an increase in soil fertility, which a cascading positive effect on the availability of habitats and resources for soil organisms. Thus, plots with understory vegetation showed a higher abundance of bacterivore nematodes and macrofauna compared to plot without understory vegetation, demonstrating the critical role of understory vegetation for soil organisms. These results indicate that the management of shrub vegetation, rather than that of the tree layer, influences soil fauna. Indeed, the suppression of understory vegetation, compared with plots where it is maintained, reduces the abundance of soil macrofauna, whether the forest thinning is moderate or intense. However, regardless of the type of forest management applied, no reduction in the abundance of soil organisms was observed compared with control plots. This indicates that, over the long term (17 years after thinning), forest management has no negative impact on soil biodiversity compared with unmanaged forests. Yet, when forest thinning is implemented, maintaining the shrub layer helps prevent a negative effect on soil fauna. These finding provide an overview of the effect of forest management practices commonly employed to preserve soil biodiversity.

Ctry	Location	Contact	Tree species	Soil type	Climate	Current management	Experimentation (treatment)	Results & findings
ES	Llobera, Secanella and Madrona (Life+ Demorgest)	**CTFC** Pere Casals Jordi Garcia	*Pinus nigra* subsp *salzmannii* (with some scattered *Pinus sylvestris* and *Quercus pubescens*)	Silt loam calcareous (developped from a calcareous limestone bedrock)	Humid Subtropical (Cfa) – submediterranean	Management on fire-prone ecosystem	Two intensities of thinning from below followed by understory clearing. Slash burning or non-burning within each thinning intensity. Non-thinned control stand at each location. Study made 5 years after the thinning and burning activities	Forest thinning had little impact on forest floor C stocks. Burning thinning residues increases tree growth and resistance to eventual fires and droughts, but partially consumes the organic layers, causing a significant loss of C, which is still not recovered 5 years post-fire. Also, burning increases the stability of C in the surface mineral soil and alters the catabolic functions of soil communities. These functions (substrate-induced respiration) are reduced where we found little amounts of C in the forest floor of the burnt stands. Previous results in which we experimentally heated soils from Llobera, indicated that soil heating reduced the catabolic functional diversity. Results from this experiment also indicate that post-fire plant growth enhance the functional recovery of soil communities.
FI	Karstula	**Luke** Aleksi Lehtonen	*Pinus sylvestris*	Sandy – sandy loamy	Subarctic (Dfc)	Even-aged management	Fertilisation since 1960 w/ NPK	Nitrogen fertilisation in boreal forests typically increases tree biomass accumulation. The impact of fertilisation to tree growth is limited in time, but typically trees can grow faster for 2-7 years after fertilisation and during that time they accumulate more foliage biomass to support their increased growth. We found that nitrogen addition increased substantially carbon stock of the organic layer of the Scots pine dominated forests. We observed higher content of C and N under N fertilisation treatment and higher concentration of stable C pool in the soil organic layer. Also, microbial biomass, necromass and activity of extracellular enzymes increased under N addition, but not greenhouse gas production. These changes were mainly observed in organic layer of the soil, but not in mineral layer. Mechanistically, N addition elevated soil C stock via increased litter input and higher transfer of C to soil microorganisms resulting in enhanced formation of fungal biomass and further necromass, which was stabilised in the soi. Nitrogen fertilisation seems a promising method as a climate smart forestry practice in boreal region when potential nutrient loading to waterways is avoided by appropriate management plans.
LT	Kacergine	**VMU** Jūratė Aleinikovienė	*Pinus sylvestris*	Poor sandy	Warm Summer Continental (Dfb)		Fertilisation w/ nitrogen	The nitrogen fertilisation did not impact significantly microbial respiration (Rh), while clearcutting resulted in significantly lower Rh, likely due to reduced soil carbon stocks. Soil microbial diversity was generally unaffected by nitrogen fertilisation. Bacterial diversity correlated positively with greenhouse gas fluxes, whereas fungal diversity showed no clear relationship

Ctry	Location	Contact	Tree species	Soil type	Climate	Current management	Experimentation (treatment)	Results & findings
UY	Tacuarembó Region	**INIA** Mario Pérez Verónica Ciganda Carolina Leoni Martin van der Abbeele Lucia Salvo Alvarez	*Eucalyptus grandis, Eucalyptus dunned*	Sandy loam, fine	Humid Subtropical (Cfa)	Afforested native grassland	Afforestation w/ eucalyptus in third rotation vs conventionally grazed native grassland	Total soil CO_2 efflux monitoring showed consistently lower carbon emissions from eucalyptus plantations compared to adjacent native grasslands. However, biological indicators revealed major shifts in microbial functioning and soil organic carbon (SOC) cycling. Trenching experiments demonstrated that autotrophic respiration (Ra), which dominated in native grasslands, was strongly reduced under eucalyptus, indicating a decoupling of root activity from surface soil respiration. In contrast, grassland soils exhibited tight coupling between root biomass, microbial respiration, and labile carbon turnover, supporting a saturated and biologically active system. Afforested soils showed reduced microbial biomass, weaker temperature–respiration coupling, and lower respiration per unit SOC. Combined with acidification of deeper layers and lower microbial biomass/SOC ratios, these results suggest suppressed microbial activity and carbon use relative to native grasslands. These changes reflect a disruption of the soil biological loop following afforestation—even in sandy soils with low SOC storage capacity. While eucalyptus plantations may reduce surface CO_2 emissions in the short term, they do not necessarily enhance carbon sequestration under current management. Moreover, impaired microbial processes may threaten long-term soil resilience. Afforestation of sandy grasslands with eucalyptus, while effective in lowering surface CO_2 efflux, presents trade-offs in terms of microbial functioning and topsoil carbon stability. Given the short rotation cycles typical of eucalyptus plantations (often <10 years), sustained belowground carbon gains may be limited if microbial activity and carbon use efficiency remain suppressed. Our findings focus on superficial soil layers, and further investigation into deeper horizons is needed to fully assess long-term sequestration potential. The climate-smart value of this land-use change will ultimately depend not just on flux reductions, but on how well it supports resilient soil biological processes over successive rotations.

2.3 Effects of treatments on windthrow, drought, and fire disturbance sites

Ctry	Location	Contact	Tree species	Soil type	Climate	Disturbance	Proposed Post-Disturbance Practice	Results & findings
NL	Ränskälänkorpi	**Luke** Raisa Mäkipää Aleksi Lehtonen	*Picea abies*	Drained fen	Subarctic (Dfc)	Wind-throw	Fallen trees and woody debris remaining in forest	Uprooting caused topsoil removal decreased CO2 emissions, but increased CH4 and N2O emissions and cause climate warming effect. Due to the removal of ground vegetation, the relative abundance of EcM fungi declined and replaced by saprotrophs. The tannins compound in soil which derived from roots was also lower. As a results, the stable organic carbon fraction was significantly decreased after 2 years deep soil exposure. The woody residues from fallen tree canopy left on site can increase CO2 and N2O emissions, resulting in climate warming effect. It inhibits fungi biomass in soil, while can help to enhance the soil carbon stabilisation by increasing the stable organic carbon fraction which offset the negative effect of topsoil removal.
FR	Saint Christol d'Albion	**AMU** Mathieu Santonja	*Quercus pubescens*	Luvisol	Mediterranean (Csa)	Drought-induced tree mortality interacting w/ thunderstorm		[Analysis ongoing; results expected October 2025]
ES	Cadiretes		*Pinus pinaster / Quercus suber*	Typic Haplo-xerept (Granites and Schists)		Fire	Standing trees remaining	Soils show a certain capacity to recover chemical properties and lost carbon after a fire (20 years), although not when fires reach severe intensities. In other words, the intensity of the fire largely determines the capacity of soil to recover functions and diversity in time. On the other hand, results show that the single best solution to protect forest soils against intense fires is the prevention. Especially in areas like the Mediterranean where fires are recurrent, this may alter substantially soil biodiversity and the capacity of forest soils to function. Controlling the amount of biomass by removal of all dead vegetation, caused by snow and winds, by setting prescribed fires or by introducing livestock are all measures that do not seem to affect the soil and that can, however, prevent high-intensity fires that later affect the soil's ability to recover over time.
ES	Cap de Creus	**UB** Xavier Úbeda	*Quercus ilex*	Litic Xerorthent (Limestones)	Steppe (Bsh)	Wildfire	Totally burnt	For the burned plot with cattle grazing in Cap de Creus, for now the most obvious effects between plots are due to the fire phenomenon, much clearer than the effect of cattle crossing, although there is still data to be processed, such as microbiological and vegetation analyses. It does not seem, now, that cattle crossing is very aggressive to the soil, and if it were, it would be proven that cattle crossing could be a way of managing the forest after disturbances such as fire. The introduction of livestock into areas that have suffered fires is advisable, as long as it is proven that it does not have a negative impact on the soil. That is why studies of this type are important. Extensive livestock farming is a practice that will increase as all administrations are encouraging the reintroduction of livestock and the training of new shepherds with aid. It can be seen how it has a positive effect on reducing fuel, and even converting areas that were forests into more open areas, where trees can be combined with pasture areas.

Ctry	Location	Contact	Tree species	Soil type	Climate	Disturbance	Proposed Post-Disturbance Practice	Results & findings
ES	Montgrí	Xavier Úbeda	*Pinus halepensis, Quercus ilex*	Litic Xerorthent (Schist and gneiss)	Steppe (Bsh)	Fire	Standing trees, woody debris remaining	In the Montgrí plot, which was burned with a low intensity fire, it can be said that the most notable effects are observed after one year of forest management, but that after two years, most parameters are adjusted to the values of the unburned control plot. We can conclude that prescribed burning is not an aggressive forest treatment for the soil. Former Pinus halepensis plantations have become high-risk fire zones due to the large accumulation of fuel. Prescribed burning, as a forest management with the aim of breaking the vertical continuity of the fuel, has been shown to be a practice that does not have negative consequences for soil properties. Even so, it is not a practice that can be carried out with too high frequency, since fire is still a disturbance, even in Mediterranean environments where fire has been shown to be another ecological factor.
ES	Gámiz	BC3 Jorge Curiel Yuste	*Quercus faginea*	Silty clay with organic layer of 0.05m	Oceanic climate (Cfb)		Standing trees remaining	[Analysis ongoing; results expected October 2025]
RO	Brasov-Dumbravita	UTBV Catalin Petritan Ioan Dutca	*Quercus robur*	Planosol	Warm-summer Humid Continental (Dfb)	Drought-induced tree mortality	Standing trees remaining	Effects of the disturbances on soil properties were lower, however 100% canopy disturbance treatments increased respiration rates, especially when slash was added to the soil. 100% canopy disturbance increased soil moisture independently of slash addition, while temperature sensitivity of soil respiration did not vary with any of the disturbance and post-disturbance treatments. Fungal and bacterial biomass did not change with the disturbance treatment that barely affected enzymatic activities in Romania. The canopy and post-disturbance treatments had the least effect on the soil In Dumbravita, which is the plot subject to longer rotation shifts (130 years), with a lower tree density, although with larger trees, overall lower bulk density and less C stocks. That is, adopting a type of forest management based on longer rotation is the best way to conserve the soil, its functioning and biodiversity in the face of a potential increase in natural disturbances to which forests will be subjected.

3. Project contributions and key messages

3.1 Project contributions

HoliSoils makes an important contribution to increasing the sustainability of forest management in Europe and beyond.

- Based on improved understanding of soil properties and processes, HoliSoils provides harmonised analysis methodologies as well as monitoring tools and best management strategies regarding key soil functions, hence **enabling widespread action to improve the status quo soil health, soil health recovery after disturbances, and soil health stabilisation across Europe and beyond.**
- Based on experimental testing across different European forest ecosystems and on projections under multiple climate change scenarios, HoliSoils provides comprehensive and balanced analysis of a variety of soil conditions and forest management practice impacts, as well as **guidance for preferable protective and remedial actions**.
- As a result of both, it facilitates **optimisation of forest soil health and forest soils' contribution to climate change mitigation** by means of a variety of reference materials and simulation models and tools. Improved GHG reporting, strategic climate smart forest management, and advanced policies at local, regional, national and EU level may result that would enable an enhanced contribution to international initiatives and commitments such as the EU carbon removals initiative and UN Sustainable Development Goals.

The project's results and contributions can be grouped into four main categories.

Improved soil understanding

- Improved soil conceptual and simulation models taking into account comprehensive soil properties and soil microbial diversity (Khurana et al. 2023; Bruni et al. 2025).
- Identification of soil processes driving GHG emissions, nutrient fluxes and decomposition.
- Improved forest ecosystem models, knowledge on feasibility and trade-offs between conventional and climate-smart forest management.
- Harmonised methods for soil property characterisation.

Data products, and data access and processing tools

- Open access data base on soil information.
- Web-based server to evaluate spatial soil data.
- EU map of disturbance-vulnerable soils.
- Map of European forest soil microbial diversity and guilds.
- Ensemble soil modelling tool.

Guidance for advanced methodologies and good practice

- Advanced methodologies for: soil analysis; harmonised, transparent and credible soil GHG monitoring and forecasting; assessing soil vulnerability and achieving degradation neutrality.
- Guidance for good practice forest management with a focus on soils in general, good practice forest management for soils after disturbances, good practice holistic soil and forest management (incl. hydrology).
- Integrate+ application for practitioners based on an improved soil model.

Recommendations for policy and decision makers

- Policy briefs on soil carbon sequestration and greenhouse gas fluxes, the beneficial effects of Climate-Smart Forestry practice for soil carbon dynamics, and on the importance of harmonised forest soil sampling and assessment for the implementation of the EU Soil Monitoring Law.
- Policy events in Brussels to present the project results and outcomes.

The project's main results and how to access them are found in section 4.

3.2 Key messages

The HoliSoils project relied on in-depth analysis of soil processes and their responses to alternative treatment at multiple test and experimental sites that represent a variety of European forest ecosystems and soil conditions (including post-disturbance sites representing the most common detrimental natural and human-induced impacts). The insights and findings from this work lead to some key recommendations for decision m akers and forest managers.

Forest soil health impacts ecosystem services

Forest soils provide multiple ecosystem services. For this. forest soils rely on complex interactions, interdependencies and feedbacks between many components and processes of soil biology, soil physics and soil chemistry – creating a unique balance that varies according to forest type.

Key message 1: Accelerated climate change and growing timber demand are putting forest ecosystems under increasing strain. Improved measures are needed to protect, maintain, and enhance soil health (stability, structure, fertility, biodiversity, etc.) and to promote forests' recovery after natural and human-caused disturbances such as clearcuts. (D4.4/4.7, D.5.2-5.3, D6.3, D2.1-2.3, D1.1-1.3, D3.5) (Bosela et al. 2025)

Key message 2: Forest management practices affect soil characteristics and processes, which in turn affect forest structure and growth. Site-specific Climate-Smart Forestry practices include optimised thinning regimes, selection harvesting, selection of tree species and mixed-stands, as well as disturbance recovery activities. Such practices protect and enhance forests' potential to provide multiple ecosystem services, such as carbon storage, biodiversity preservation and long-term productivity. (D2.1-2.3, D4.2/4.4/4.7, D5.2-5.3, D6.3) (Mäkipää et al. 2023)

Key message 3: Forest soils are complex and vulnerable to many kinds of degradation and disturbance - both natural ones and those caused by humans. To protect or restore them, practical tools informing interventions need to consider soil microbiology, soil biogeochemistry, soil physics, and soil hydrology, as well as the complex feedbacks between them. It is essential to protect soil biodiversity and especially soil fauna that facilitate soil water access, carbon sequestration and top-down trophic effects. Once the damage is done, recovery requires intervention and time. (D2.1-2.3, D1.5, D5.4) (Martin et al. 2024; Pérez-Izquierdo et al. 2025)

Forest soils contribute to reaching environmental goals

Forest soils play a crucial role in reaching goals on climate change mitigation and halting biodiversity loss. They host essential biodiversity, and they store and sequester significant amounts of carbon, often holding more carbon than the vegetation above them. By accumulating organic matter from decomposing plant material and root systems, forest soils act as long-term carbon sinks, stabilising carbon for decades to centuries. In contrast, vegetation, such as trees and undergrowth, stores carbon more dynamically, with faster uptake during growth and more rapid release through decay or disturbance. While vegetation is vital for capturing atmospheric carbon through photosynthesis, forest soils provide a stable and enduring reservoir, making both components essential but complementary in the global carbon cycle.

Key message 1: It is often overlooked that forest soils are a locus of both carbon sequestration and storage, and important biodiversity. Adjusting forest management practices, e.g. varying stocking density, thinning intensity and frequency, and rotation length, as well as adopting sustainable post-fire management practices, can increase soil carbon stocks or reduce greenhouse gas emissions. (D4.2/4.4/4.7, D4.6, D.5.2-5.3, D6.3) (**Mäkipää et al. 2023**; **Pérez-Izquierdo et al. 2025**)

Key message 2: Forest soils across Europe hold varying yet significant potential to contribute to climate change mitigation and play a role in addressing other urgent environmental concerns such as biodiversity loss. To harness this potential, science-based long-term and multi-scale soil monitoring of soil carbon sequestration and GHG emissions is recommended, along with policy-backed and locally tailored practices. These include restoration of carbon-rich soils, protection and promotion of biodiversity, and sustainable forest management practices such as mixed-stands, selection harvesting and continuous cover forestry. (D1.1-13, D2.1-2.3, D3.5, D4.4/4.7, D5.2-5.3, D6.3).

Key message 3: Forest soils across Europe face the risk of becoming net carbon sources. Carbon stocks in Mediterranean forest soils are acutely vulnerable to climate change induced changes in precipitation. Carbon stocks in boreal peatland forest soils are vulnerable due to deep drainage that has reduced water content and increased aeration, making organic matter more prone to decomposition. Strategies for soil health conservation and disturbance recovery, including through regulation of forest management practice, are critical to ensure continued soil function and carbon storage. (D5.2-5.3, D6.3) (**Escobar et al. 2022**)

Forest management impacts soil health

Forest management practices affect soil health, carbon storage, and greenhouse gas emissions differently across diverse forest ecosystems. Climate-Smart Forestry practices and other alternative practices, such as prescribed burning, can have beneficial impacts when compared to conventional forestry for soil function, resilience, and sustained productivity, as well as for carbon sequestration and emissions reduction. Forest management can be optimised according to these considerations.

Key message 1: Clearcuts have a strong negative effect on soil carbon and soil functioning, notably in forests on peatlands. Regulating forest management and replacing conventional practices with locally tailored Climate-Smart Forestry and disturbance recovery activities can help prevent this. (D4.2/4.4/4.7, D5.3)

Key message 2: In fire-prone regions, prescribed burning increases resistance to wildfires as well as to severe drought, but, depending on the fire intensity of the prescribed burn, may have neutral or negative impacts on soil carbon stocks. Well-informed, sustainable pre-and post-fire forest management practices can enhance soil health and microbial recovery after wildfire events. (D4.2, D5.3, 5.2)

Key message 3: Most forest owners consider soil health important. A sizable majority of forest owners who are not already applying Climate-Smart Forestry practices are open to testing or adopting such practices. Carefully designed financial incentives may support wider adoption of practices to enhance soil health, but full adoption may require additional interventions. (D4.6)

Advanced forest soil monitoring is needed

Critically, 60–70% of EU soils are degraded. This affects soil's ability to contribute to climate change mitigation, but also soil's importance for provisioning of ecosystem services and biodiversity. Soil degradation costs the EU tens of billions annually, and healthy soils are vital for achieving SDGs and the EU Green Deal goals. In order to inform realistic policy and strategic action, reliable data and information is indispensable – particularly about forest soils.

Key message 1: Growing recognition of forest soils' capacity to sequester and store carbon means that harmonised soil monitoring, reporting and compliance standards, and data sharing are fundamental for comparability and reliability of assessments of progress towards these targets. (D1.1-1.3, D3.5)

Key message 2: The EU Soil Monitoring Law is a welcome initiative. For its effective implementation, a methodology that captures the features and dynamics of forest soils (including forest floor and peat soils) alongside other soil types is needed. (D1.1-1.3, D3.5)

Key message 3: Forest soil processes take time and are subject to great variability. To understand them and their impacts in terms of ecosystems service provision – such as carbon storage – more fully, a science-based, long-term, multi-scale (forest) soil monitoring framework is needed. (D1.1-1.3, D3.5, D5.3-5.4, D4.4/4.7)

Part 2

4. Project results for policy makers

Results overview:

i. A web portal of maps, databases, process charts, infographics, and other information on soils across Europe.

ii. Practical tools for forest management for soil health, including best practice guidance for forests across Europe and a mobile application for local practical use.

iii. Best practice guidance for post-disturbance forest management for soil health.

iv. A set of maps of Europe showing soils' vulnerability to natural disturbance.

v. A web-based platform for simulation of forest dynamics under different forest management practices.

vi. Guidance on a harmonised methodology for forest soil sampling and assessment.

i. A web portal provides public access to a collection of insights and information on forest soils across Europe

In a nutshell

A continuously updated, free and easy-to-use web portal hosts a variety of visual materials, such as maps, infographics, and databases, providing the latest insights and information on forest soils across Europe and beyond. The material presented ranges from: baseline information about important parameters of soil function and properties across different European countries; illustrations of complex soil processes; data on soils' vulnerability to degradation and carbon loss; predictive yield and resilience scenarios combining different climate pathways with different forest management approaches.

Put it to use!

Policy makers can use this web portal to familiarise themselves with the state of forest soils in Europe, and to feed relevant up-to-date insights and information on this topic into their work in agricultural and forestry-related, environmental conservation, climate adaptation and climate change mitigation activities.

Technical details

The web portal contains information on:

- Europe-wide maps of forest soil properties in 100 x 100 m resolution
- Map of drained peatlands of the Baltic Sea region
- Maps on soil vulnerability
- Link to the Global Fungi Database
- Guidelines for Soil Sampling for GHG reporting, including a section on biodiversity

Find related project deliverable(s) here:

- **[Publication of Deliverable 3.7 pending]**

Find the tool here:

- **https://atlas.thuenen.de/holisoils**

Further information

- Database of EU soils' vulnerability to the most important natural disturbances (Data)
- Deckmyn et al. (2020)
- Dashboard of soil information
- Map of global fungi distribution
- Database of EU soils' vulnerability to the most important natural disturbances (Deliverable report)

ii. Climate-Smart Forestry practices help improve forest management for soil health and productivity, carbon sequestration and storage, and reduced greenhouse gas emissions

In a nutshell

Experiments in diverse forest ecosystems across Europe and beyond (representing a range of climate conditions, soil types and management strategies) show the impacts of management practices on forest soil health, as well as soil carbon dynamics and greenhouse gas emissions; Climate-Smart Forestry practices have been shown to be more beneficial compared to conventional forest management approaches. Based on this finding, good practice guidance and a mobile App are available to help forest managers make informed management choices.

Put it to use!

Policy makers who want to promote the reduction of greenhouse gas emissions and ensure carbon sequestration and storage in forest soils, as well as foster sustainable forest soil health and productivity, should incentivise Climate-Smart Forestry and disturbance recovery interventions. They should also facilitate (for instance, by funding provision and remit definition, activities and reporting protocols) additional long-term monitoring of the impact of management practices (including the effectiveness of Climate-Smart Forestry) on forest soils' carbon and greenhouse gas dynamics in order to validate and further develop knowledge in this area.

Technical details

Examples of conventional management versus Climate-Smart Forestry practices:

Business-as-usual approach	Climate-Smart Forestry alternative
Rotation Forestry: Regular even-aged management with clear-cutting and replanting, causing soil disturbance during harvest operations, and reducing carbon storage.	Continuous-cover forestry (CCF) with selective harvesting to maintain multistorey structure and canopy cover and to reduce soil degradation and CO_2 emissions, especially from peat soils.
Single-species stands with uniform age; low biodiversity, high pest/ drought vulnerability.	Mixed-species and uneven-aged forests for greater resilience, biodiversity, and potentially also for carbon sequestration.
High-intensity thinning: Heavy tree removal leading to temperature/moisture fluctuations and increased greenhouse gas emissions.	Moderate thinning to maintain canopy cover and balance soil temperature and moisture.
Heavy use of Nitrogen fertilisation (in some parts of Europe): Applying synthetic fertilisers, increasing nitrous oxide emissions and disturbing microbial activity.	Organic amendments (e.g., biochar) and site-adapted Nitrogen fertilisation to sustain soil health with lower emissions.

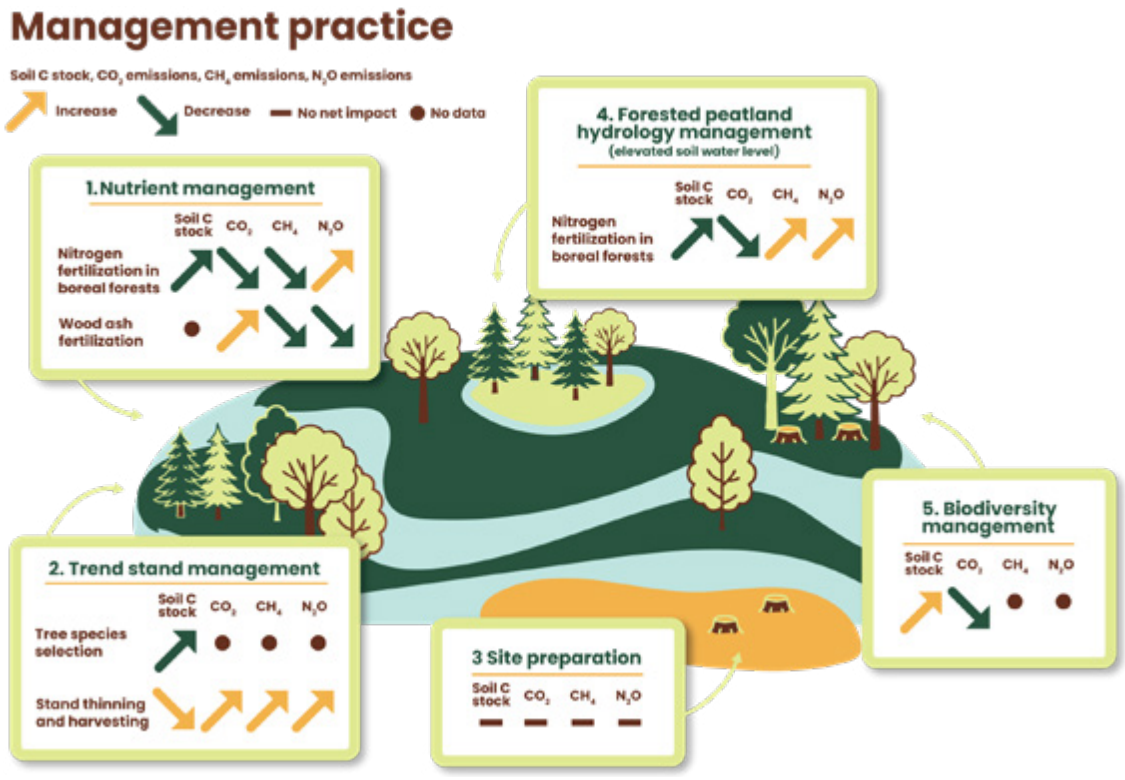
Business-as-usual approach	Climate-Smart Forestry alternative
Fire suppression without fuel management: Preventing fires but allowing fuel buildup, increasing severe fire risks.	Controlled burns or mechanical fuel removal to reduce fire risk and protect soil carbon.
Draining peatlands for timber production, increasing CO_2 emissions and reducing methane sinks.	Rewetting or maintaining natural hydrology to protect peat carbon storage.

What practices constitute Climate-Smart forestry (CSF) depends on the context (specific ecosystem and management objectives), but it is, broadly speaking, preferable to conventional forest management practices:

- The adoption of Climate-Smart Forestry, such as Continuous-Cover Forestry and selection harvesting on peatland forests, enhances soil stability and reduces greenhouse gas emissions that relate to clear-cut operations, because it reduces soil disturbance, helps to avoid ditching, and regulates soil temperature and moisture, which reduces soil CO_2 emissions.
- Drought and forest disturbances significantly alter soil carbon dynamics by impacting root respiration and microbial activity directly, and indirectly through temperature changes, increasing CO_2 emissions and decreasing methane oxidation.
- Mixed-species forests exhibit greater resilience than monocultures in terms of carbon sequestration and methane oxidation capacity. Broadleaf species, when mixed with conifers, improve soil structure and organic matter content, supporting microbial communities that contribute to higher methane oxidation rates. They are also less vulnerable to drought and pest outbreak, which lead to carbon loss.

- Forest management practices such as thinning, prescribed burning, and understory vegetation management affect soil biodiversity and carbon storage in complex ways (directly and via fire disturbance reduction) and the right balance of (moderate) interventions must be applied to maximise beneficial outcomes for soil health and climate change mitigation objectives.

- While short-term studies show that Climate-Smart Forestry practices can improve forest resilience and soil carbon retention, long-term monitoring is necessary to assess their effectiveness. To refine strategies for maximising carbon sequestration and reducing greenhouse gas emissions, future research should delve deeper into the question how Climate-Smart Forestry impacts vary across different climate zones, soil types, and management intensities.



Comparing the effects of different management practices. Source: Mäkipää et al. 2023

A mobile phone App called I+ provides users with the opportunity to understand the future impact of different management practices on different kinds of forest ecosystems. The App is based on a large network of well-understood test sites called Marteloscopes and features a new module to demonstrate soil carbon effects of Climate-Smart Forestry compared to conventional forest management.

Find related project deliverable(s) here:

- **[Publication of Deliverable 4.7 pending]**
- **[Publication of Deliverable 4.8 pending]**

Find the tool here:

- **[Publication of guidance document pending]**
- **I+ App**

Further information

- Policy brief: Forest Soil Challenges in Europe
- Policy Brief: Forest soils can increase climate change mitigation with targeted management
- Marteloscopes Information
- Biryol et al. (2024)
- Pérez-Izquierdo et al. (2025)
- Bosela et al. (2025)
- Mäkipää et al. (2023)
- Lehtonen et al. (2023)
- Helama et al. (2025)
- Tikkasalo et al. (2025)
- Lehtonen et al. (2025)
- Mäkipää et al. (2024)
- Richy et al (2024)
- Ťupek et al. (2024)
- Palvi et al. (2025)

iii. Good practice for enhancing post-disturbance forest soil recovery should be embedded in policy

In a nutshell

Good practice guidance for soil recovery following common disturbances is based on assessment of various post-disturbance management techniques across diverse European forest ecosystems.

It identifies effective strategies to conserve and restore soil health, biodiversity, and ecosystem services in the face of wildfires, windthrow, and canopy loss.

- Fire-affected areas: prescribed burning, controlled livestock grazing and selective removal of dead vegetation
- Canopy loss: avoiding clear-cutting, retaining woody debris and longer rotation cycles
- Windthrow: minimising soil disturbance and avoiding excessive biomass removal

A new model of the interplay of different soil properties in creating soil resilience has been developed, based on field experiments, and embedded in a land surface model to allow predictions of soil health and, with it, forest health.

Put it to use!

Results show that implementing post-disturbance management practices can accelerate soil recovery, and reduce biodiversity and carbon losses. Policy makers should note that evidence-based forest management policies that prioritise the conservation of soil health are needed and should be emphasised. These findings align with EU climate policies, biodiversity strategies, and forest resilience frameworks, offering actionable insights for legislative and regulatory initiatives.

Technical details

Experiments were conducted at varied European sites representing diverse forest ecosystems. The effects of various post-disturbance practices, including salvage logging and alternative management techniques aimed at restoring soil structure, nutrient cycles, and microbial communities were applied and monitored.

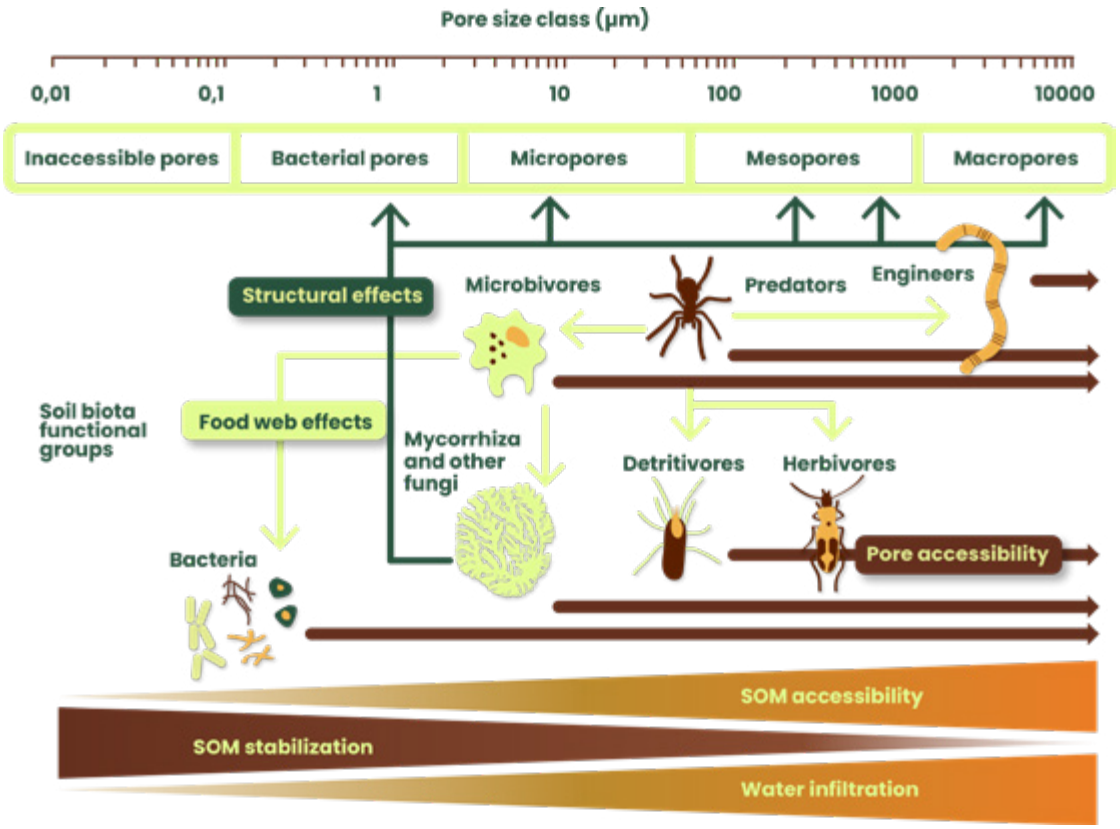
An overview of the results of the empirical study and the resulting post-disturbance management recommendations can be found below:

Disturbance type	Key effects & recovery time	Best management practices	Further explanation
Fire (Mediterranean sites)	**Effect:** Short-term impact on soil; recovery possible within decades if fires are not too severe or frequent. Prescribed burning has minimal negative effects. **Recovery:** Decades if unmanaged, faster with prescribed burns or grazing.	Prescribed burns, selective removal of fuel, and controlled livestock grazing.	Fire intensity determines soil recovery speed. Soils exposed to low-intensity fires recover faster, while severe fires damage soil for decades. Prescribed burns and grazing prevent fuel buildup, reducing fire severity and improving resilience.
Canopy loss (Spain, France, Romania)	**Effect:** Canopy removal leads to increased soil temperatures and moisture fluctuations. Slash retention improves microclimate, biodiversity, and carbon storage. **Recovery:** 2-3* years show limited recovery; long-term effects depend on slash management.	Avoid clear-cutting, retain slash to aid soil health recovery, and implement longer rotation cycles.	Canopy removal disrupts soil microclimate and biodiversity. Slash retention stabilises temperature and moisture, providing also fresh organic matter (carbon and nutrients) to aid soil biotic communities and plant recovery. Without intervention, soil may take longer to regain stability.
Windthrow (Finland)	**Effect:** Tree uprooting exposed deeper soil layers, making them vulnerable to carbon loss. Residue cover temporarily increased CO_2 and N_2O emissions but helped stabilise soil organic carbon long-term. **Recovery:** Early recovery signs after 2 years.*	Leaving woody debris to stabilise carbon, minimising soil disturbance post-event.	Windthrow exposes deeper soil, leading to carbon loss and increased greenhouse gas emissions. Residue cover initially raises emissions, but later supports carbon sequestration and microbial recovery, stabilising soil over time.

Examples of measurement and monitoring setup, Kranzberg Forest, Germany

Data collection focused on soil carbon content, moisture retention, microbial activity, and biodiversity indicators to evaluate recovery effectiveness. The comprehensive monitoring of different properties of the soil system that the experimental design rest on springs from the understanding that soil conservation and restoration must be viewed from a holistic perspective, taking into account physical (soil structure), chemical (e.g. soil carbon and nutrients), and biological (soil biodiversity) properties, which are closely connected and interrelated.

The insights from the experiments inform a new model called KEYLINK (see illustration below). It brings together soil functional diversity and food webs to predict soil carbon and soil water balances. By integrating KEYLINK into a land-surface model (ORCHIDEE), it becomes possible to predict soil health and forest health while paying due attention to soil biodiversity as an important factor in the functioning of forest ecosystems.



The interaction of soil structure, biodiversity and carbon dynamics that is at the core of soil resilience. (SOM: soil organic matter) Deckmyn et al. (2020)

Find related project deliverable(s) here:

- **Best Practices for Improving Soil Recovery Capacity after Disturbances (Deliverable report)**
- **[Publication of Deliverable 5.4 pending]**

Find the tool here:

- **[Publication of guidance document pending]I+ App**

Further information

- Pérez-Izquierdo et al. (2025)
- Deckmyn et al. (2020)
- Flores et al. (2021)

iv. Insights into EU forest soils' vulnerability to climate-induced disturbances

In a nutshell

The "Database of EU Soils' Vulnerability to Natural Disturbances" provides public access to high-resolution insights into how climate-induced changes in precipitation affect soil carbon and nitrogen stocks. Presented as a set of maps, it identifies regions most at risk of the detrimental impacts of increased droughts and extreme precipitation events. It identifies the Mediterranean region as a priority area for remedial forest management and soil conservation as it faces severe risks of soil carbon depletion and subsequent detrimental effects over its capacity to sustain biodiversity, soil functions and forest productivity. In the longer term, boreal forest soils are at risk of transitioning from carbon sinks to carbon sources under changed climatic conditions.

Put it to use!

This set of maps can help policymakers, environmental agencies and regulatory bodies to align forest and land management policies with the EU's climate mitigation goals, and to develop adaptation strategies, soil conservation policies, and sustainable forest management frameworks. It can be used to promote adaptation measures that enhance soil resilience and maintain the ecological stability of forests across Europe in a changing climate, as well as to support their role in carbon sequestration. Specifically, it can be used to support advocacy for prioritising conservation efforts for forest soils of the Mediterranean region, while continuing other important climate change mitigation work in order to avoid that even boreal forests turn from carbon sinks into carbon sources.

The maps enable evidence-based decision-making and cross-sectoral policy development by pinpointing vulnerable regions, helping to prioritise conservation funding, underscoring the importance of soil conservation, fostering sustainable land use, guiding afforestation efforts, strengthening climate adaptation initiatives and ensuring ecosystem service protection within the European Green Deal framework.

Technical details

Compiling experimentation results from different European forest types, to assess soil vulnerability under different climate scenarios, this publicly accessible collection of maps provides high-resolution insights into how climate-induced changes in precipitation affect soil carbon and nitrogen stocks. Using advanced statistical modelling techniques, it reveals significant regional disparities and identifies regions most at risk due to increased droughts and extreme precipitation events. Specifically, Mediterranean forests emerge as particularly at risk, as – under drought conditions –

they may face severe soil carbon depletion and a reduced capacity to sustain biodiversity and productivity. Hence, remedial forest management and soil conservation action is most urgently needed in the Mediterranean region. Boreal forests, which used to be carbon sinks, may also turn into carbon sources due to forest use and unsustainable management. Furthermore, risks of forest disturbances and loss of stored carbon are higher in changing climate. The database and its findings are critical for shaping EU climate adaptation strategies, soil conservation policies, and sustainable forestry management frameworks, ensuring the long-term resilience of forest ecosystems and their role in carbon sequestration and biodiversity conservation.

Find related project deliverable(s) here:

- Database of EU soils' vulnerability to the most important natural disturbances (Deliverable report)

Find the tool here:

- **[Publication of database of maps pending]**

Further information

- Database of EU soils' vulnerability to the most important natural disturbances (Data)

v. Prediction tool for forest soils' response to climate and land use changes

In a nutshell

This tool enables policymakers and experts to simulate how forest soils carbon stocks will behave under different climate pathways and land management approaches, taking into account advanced information like soil texture, air or soil temperature and hydrology.

It uses six scientifically recognised models to estimate carbon storage and emissions of key greenhouse gases. The web-based tool is user-friendly and designed to inform science-based decision-making, but the model is also accessible via expert tools.

Put it to use!

The tool empowers public agencies to test the long-term outcomes of forestry practices and disturbances like fire or disease, facilitating design and promotion of climate-smart land use policy. Policy makers can use the tool to support climate action planning, inform land-use regulation, guide national GHG inventories, and align strategies with EU Green Deal targets.

Technical details

The interface and analogous tools integrate six models: Century, Roth-C, ICBM, Yasso07, Yasso20, and the SG model. This multi-model ensemble simulates soil organic carbon (SOC) and emissions of CO_2, CH_4, and N_2O. The tool works with user input or automatically pulls data from global databases, allowing site-level simulations under IPCC climate scenarios, land-use trends, and forest management disturbances. The model may be operated locally via the R software package and is included more models based on newly developed hypothesis, but an accessible online (web browser-based) version is also available that gather only the more robust models.

Find related project deliverable(s) here:

- Model Ensemble Script
- Online Model Launching Interface

Find the tool here:

- Web interface

Further information

- Further relevant Deliverable reports

vi. Harmonised methodologies for Pan-European forest soil assessment and biodiversity monitoring

In a nutshell

A set of harmonised methodologies for assessing soil nutrient stocks, organic matter properties, biomass of soil organisms, and biodiversity in European forest soils. These methodologies aim to standardise data collection across EU countries, ensuring consistency and comparability in greenhouse gas reporting and enhancing soil health monitoring. Moreover, they have the potential to significantly improve EU soil monitoring legislation by providing an approach that is suitable to capture the idiosyncrasies of forest as well as agricultural soils.

Put it to use!

Integrating these methodologies into national soil monitoring programmes can help to facilitate compliance with EU and international environmental policies. In addition to promoting standardisation, these methods improve reporting accuracy for soil carbon concentration and stocks and biodiversity, facilitating the production of reliable data to guide sustainable land management and biodiversity conservation strategies, and aiding evidence-based policymaking as well as formulation of climate action strategies.

Technical details

The proposed framework integrates:

- Soil Nutrient Stock Assessment: Standardised protocols for precise soil sampling techniques and laboratory analysis of essential soil nutrients such as nitrogen, phosphorus, and carbon across EU countries.

- Organic Matter Characterisation: Methods for identifying soil carbon fractions and their response to forest management, including techniques that help distinguish between stable and decomposable carbon pools, providing valuable insights into long-term carbon storage and the effectiveness of forest management practices in maintaining an equilibrium of soil carbon fractions.
- Biomass Quantification: Advanced techniques for assessing the biomass and composition of soil biota—including microbial communities as well as micro-, meso-, and macrofauna—providing insights into the specific groups responsible for nutrient cycling, soil fertility, and ecosystem resilience.
- Biodiversity Monitoring: DNA analysis is recommended to asses the diversity of soil organisms, enabling large-scale biodiversity assessments and understanding of how different land management practices affect soil biodiversity and ecosystem stability.

Find related project deliverable(s) here:

- Harmonised methodologies for assessing soil nutrient stock
- Methodologies for characterisation of soil organic matter properties & identification of those responding to forest management
- Harmonised methodologies for quantification of biomass of key trophic groups
- Harmonised methodologies for analysis of soil biodiversity, functional redundancy & community resilience in forest soils

Find the tool here:

- Soil monitoring guidelines

Full information

- HoliSoils project website
- HoliSoils project CORDIS page

Further information

- Policy brief: How to advance the implementation of the EU Soil Monitoring Law?
- EU Soil Monitoring Law information
- IPCC Guidelines on GHG Inventories
- Why monitoring forest soils is important

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