SUPERB

Upscaling Forest Restoration

D6.4 Soil Restoration and Monitoring Guidelines

Guidelines for the integration of soil health in forest restoration: insights from SUPERB

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DISCLAIMER

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Summary

Forests are essential ecosystems, covering approximately 35% of Europe's land area. They harbor a significant share of Europe's terrestrial biodiversity and provide a wide range of ecosystem services critical to European citizens. However, forests across Europe are increasingly threatened by various forms of degradation, driven by multiple, often anthropogenic factors. Many of these degradation processes originate or manifest within the belowground ecosystem compartment. Given that an estimated 3% of European soils are already degraded, decreasing soil health may represent a fundamental underlying cause of forest decline. Despite the growing recognition of the need for forest restoration, comprehensive guidelines that integrate soil health into monitoring and restoration practices remain limited. Within the framework of the EU Horizon 2020 SUPERB project, we have gained valuable insights into how restoration efforts - across varying scales and contexts - impact belowground ecosystem dynamics. This report provides a synthesis of the main findings derived from our work conducted within the framework of the SUPERB project. We illustrate the findings in an integrated table discussing expected impacts of restoration measures on physical, chemical, and biological aspects of soil health. Additionally, we propose a monitoring scheme for selected scalable indicators to support long-term assessment of soil health. We emphasize the need for context-explicit restoration measures that take into account the inherent capacity of the soil, rather than applying blanket treatments.

Keywords

Soil health, forest restoration, monitoring, soil carbon, forest ecosystem services

1. Introduction

1.1 Importance of conserving forests and avoiding forest degradation

Forests cover approximately 31% of the Earth's land surface, support the livelihoods of millions, and harbor the majority of terrestrial biodiversity. Healthy forests provide a wide range of ecological, economic, and social benefits that sustain more than 8 billion people (De Groot et al., 2002; Jenkins & Schaap, 2018). Among these many ecosystem services, forests play a crucial role in climate mitigation by capturing carbon dioxide from the atmosphere and storing it in living and dead biomass both above and belowground (Jenkins & Schaap, 2018; Whitehead, 2011). Forest soils, in particular, are the largest terrestrial reservoir of organic carbon (European Commission, 2011; FAO, 2020) with European forest soils estimated to store between 1.5 (EC/UN-ECE et al., 2003) and 2.5 (De Vos et al., 2015) times more carbon than trees themselves. Most of this carbon is stored as organic matter in the forest floor and mineral soil. Maintaining healthy soils is essential for sustaining healthy forest ecosystems. But what is soil health? **Soil health is defined as 'the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans"** (U.S. Department of Agriculture, 2012).

Despite their importance, forests worldwide are under increasing pressure, with global forest area in decline and signs of widespread degradation, including increased defoliation, dieback, and loss of forest-associated biodiversity (FAO, 2022; IPBES et al., 2019). About 3% of European forests are damaged and as forest health deteriorates, so does its capacity to provide ecosystem services; degraded forests may even shift from being carbon sinks to carbon sources (FOREST EUROPE, 2020). Forest degradation is intrinsically linked to soil degradation. Without healthy soils, forests cannot perform essential ecological functions, from carbon storage to biodiversity support. For this reason, forest restoration can never be considered in isolation from forest soil health and forest soil restoration.

In this context of increasing pressures, the **conservation of existing forests and the maintenance of their habitats in a good state of conservation must be the top priority**: preserving forests is a crucial first step in maintaining ecosystem stability, mitigating climate change and safeguarding biodiversity (Pawar & Rothkar, 2015). Moreover, protecting intact forest ecosystems is far more feasible, effective and cost efficient than trying to restore degraded ones.

1.2 Forest degradation and its impact on soil health

Despite the importance of forest conservation, extensive degradation continues. Globally, 420 million hectares of forest were lost to deforestation between 1990 and 2020, and although the global deforestation rate have recently declined, an estimated 10 million hectares were still lost annually between 2015-2020 (FAO, 2022). In Europe, forest cover is steadily increasing, and recent management strategies have been somehow effective in improving the overall forest conditions, such as an increased in deadwood volume, forest area, biomass volume, and overall productivity. Nonetheless, forest habitat degradation remains ongoing proxied by increasing defoliation (FOREST EUROPE, 2020), foliar nutrient imbalances (Jonard et al., 2015) and decreasing tree cover density and species richness of threatened birds (EEA, 2024; FOREST EUROPE, 2020; Maes et al., 2023).

This aboveground degradation is mirrored belowground or could potentially be driven by belowground degradation. Soil acidity levels have remained constant (too acidic), soil nitrogen levels remain excessive despite decreases in deposition (FOREST EUROPE, 2020; Van Groenigen et al., 2017), and soil organic carbon keeps decreasing (Maes et al., 2023). Soil degradation - whether chemical (e.g., acidification, eutrophication, nutrient depletion), physical (e.g., erosion, compaction), or biological (e.g., loss of biodiversity) - is weakening soil fertility, impairing nutrient and water cycling, reducing carbon sequestration capacity, and undermining forest resilience and sustainability. Overall soil health is declining on a European scale (European Soil Data Centre, 2025). These trends are primarily driven by threats such as anthropogenic pressures (including those that affect belowground ecosystem such as eutrophication, acidification and overexploitation) in addition to severe climatic events (e.g. drought and wildfires), new pests and diseases, and other environmental disturbances (Ameray et al., 2021; FAO, 2020; IPBES et al., 2018; Mäkipää et al., 2023; Scanes, 2018).

In summary, healthy soils are the foundation of ecosystem restoration, and their continued decline underscores the urgent need for integrated forest-soil strategies that explicitly prioritize soil health (Maes et al., 2023).

1.3 Importance of integrating soil health into forest restoration

When soil conservation failed and soils are degraded as a part of overall forest degradation or as the prime cause, **soil restoration** is essential (Maes et al., 2023). It is clear that, **forest- and soil restoration are deeply interconnected**, as soil health directly influences forest recovery and long-term ecosystem stability (Raupp et al., 2024). Restored forests contribute to organic matter accumulation, soil stability and improved nutrient cycling, leading to an enhanced carbon sequestration, biodiversity conservation, and climate resilience. Conversely, when soils are degraded forest recovery can be hindered (Jenkins & Schaap, 2018; Jiba et al., 2024; Page-Dumroese et al., 2021; Powers et al., 2015).

Such **integration is also essential within restoration frameworks**. In recent years, there has been a surge in policies aimed at forest and soil restoration (Cliquet et al., 2022; Mansuy et al., 2022). One prominent example is the European Green Deal, a strategic initiative designed to make Europe climate-neutral by 2050. As part of this initiative, the Nature Restoration Law establishes legally binding restoration targets for EU member states, aiming to restore at least 20% of the EU's land and sea areas by 2030 and all degraded ecosystems by 2050. On a global scale, initiatives like the Bonn Challenge - which seeks to restore 350 million hectares of degraded and deforested land by 2030 - and the UN Decade on Ecosystem Restoration - which mobilizes governments, communities, and businesses to take action - also play a vital role in addressing environmental degradation. Despite these efforts, restoration activities often prioritize above-ground biomass, such as tree growth and canopy cover, while neglecting critical below-ground components (Aerts & Honnay, 2011; Farrell et al., 2020). This imbalance can undermine the long-term success of restoration efforts (Nolan et al., 2021).

How forest issues are defined is shaped by ecological and socio-ecological contexts, as well as the values and beliefs of different stakeholder groups. Understanding these diverse perspectives is essential for effective forest restoration implementation in Europe, especially where conflicting views may lead to disagreement (O'Brien et al., 2025).

1.4 When & Where? Restoration is context dependent!

The success of measures focus on forest restoration and soil restoration vary considerably and are underpinned by site conditions and context. This means that a one-size-fits-all approach is not possible and site characterization is fundamental for successful restoration (Hobbs & Harris, 2001). To make this context-dependency clear, we adopt the framework of McBratney et al. (2014, 2019) who introduces five key dimensions of soil value with **capacity**, referring to the soil's inherent potential, and **condition**, referring to the current state of soil health, as most **important in the context of practical restoration**. The other dimensions refer to **capital**, reflecting the economic worth of soils influenced by markets, productivity, and land ownership; **connectivity**, emphasizing the role of knowledge, resources, and interactions with environmental and social systems in maintaining soil health; and **codification**, involving the policies and knowledge systems that guide soil management, varying by region and culture, but are not used in the below described guidelines. Together, these dimensions highlight that effective and sustainable soil management depends on local context and a long-term approach (A. McBratney et al., 2014; Alex. B. McBratney et al., 2019).

First, it is important to evaluate the inherent potential of certain sites and establish a baseline. Therefore we adopt the concept of soil **capability** that refers to the soil's inherent potential to perform specific functions such as supporting plant growth and ecosystem services, which varies with local climate, topography, and soil type. Capability is shaped by decades of land evaluation research and contains a set of long time-scale or very slowly changing characteristics. For example, soil texture greatly determines the potential of a certain site for forest ecosystem functioning as it affects overall soil fertility, water holding capacity, acid buffering capacity. Yet soil texture is not a variable that can be (easily) changed through management and is therefore a fixed boundary condition to understand a certain soil condition. Second, soil **condition** encompasses the latter, i.e. the manageable physical, chemical and biological soil properties to assess the current state of the soil, influenced by land use practices, pollution, and conservation efforts and is being assessed on a short-term management timescale. The condition of the soil refers to its ability to function within land use and ecosystem boundaries and will vary to how it is managed. A combination between condition and capability results in the productivity/performance of the soil. Effective monitoring can only be executed when both soil capability as soil condition are evaluated.

2. Aim and methodology

This report aims to provide a comprehensive overview of the lessons learned from SUPERB and general guidelines for forest restoration, with a particular focus on restoring and monitoring soil health after forest and soil restoration measures are taken. By addressing three fundamental questions: **what to restore** (focus on soil properties), **how to restore** (focus on measures that target forest and soil restoration), **and how to monitor** restoration efforts (focus on soil capacity and condition) we aim to integrate the dual aspects of soil within forest ecosystems. By **disentangling the concepts of soil capacity and soil condition**/health we emphasize the importance of context when taking a certain measure and monitoring its impact.

2.1 SUPERB project

These guidelines are part of the European Union's Horizon 2020 SUPERB project, which aims to restore thousands of hectares of forests in Europe. Through a predetermined field set-up in 12 European countries (Figure 1), soil samples were taken, covering various stages of restoration. This comprehensive soil sampling provided valuable data and insights, which formed the basis for the recommendations and strategies outlined in this report.

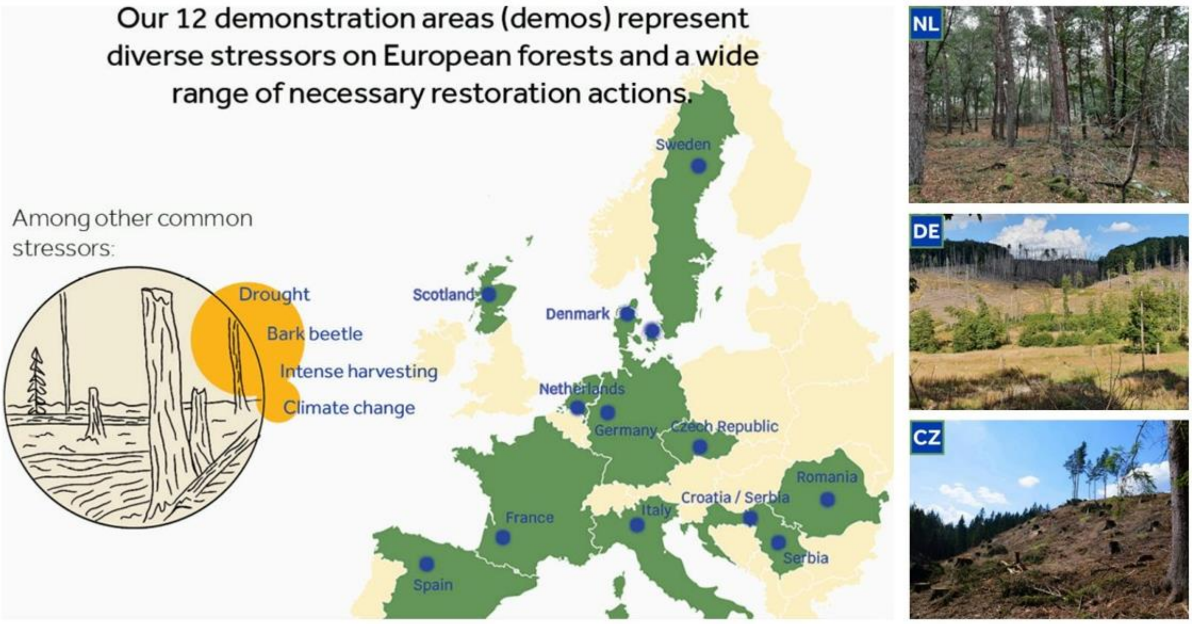


Figure 1: Overview of the SUPERB project network: 12 demonstration areas representing different degradation problems and restoration challenges across Europe. Illustration by SUPERB (SUPERB, 2024).

2.2 What to restore?

Although we adopt a clear definition of soil health in this report (see section 1.1), it does not come with specific guidelines for how to measure or monitor it in practice (Fierer et al., 2021). Particularly, which variables are most relevant to assess the soil's condition. It is clear that soil health cannot be defined by a single 'optimal' state, as it varies across ecosystems and land uses (Bünemann et al., 2018; Lehmann et al., 2020). Still, certain indicators are consistently useful for assessing soil health. For instance, healthy soils typically are well-structured (physical health/condition), contain sufficient SOC to bind water and nutrients (chemical health/condition) and are full of life (biological health/condition) (Frene et al., 2024; Raghavendra et al., 2020; Stewart et al., 2018; Wang & Zhang, 2024). Effective soil restoration addresses these three key categories of soil properties, i.e. physical, chemical, and biological (Raghavendra et al., 2020; Stewart et al., 2018). In this chapter, we propose a set of indicators for each category, some of which are considered 'scalable', i.e. designed to be applicable across diverse ecosystems, cost-effective, and easy to implement. Table 1 provides an overview of scalable physical, chemical and biological indicators, and 'nice-to-have' indicators. Indicators shown in bold represent those measured in the SUPERB project.

Table 1: Scalable and 'nice-to-have' physical, chemical and biological indicators. Indicators shown in bold represent those measured in the SUPERB project.

	Physical	Chemical	Biological
Scalable indicator	**Bulk density**	**Carbon**	**Metabolic activity**
	Aggregate stability	**Nitrogen**	
		pH	
		EC	
Nice-to-have	Water holding capacity	CEC	**Catabolic microbial activity and diversity**
	Water infiltration rate	Specific nutrient status (NO3-, NH4+, P, K, base cations)	**Biomass fine roots**

2.2.1 Physical properties

Within the physical properties we propose to evaluate bulk density and aggregate stability as they influence the interconnectivities between plants and soils and can be influenced by human activities. Soil texture is also an important physical measure, yet as it is not variable under management it proxies more the soil's capacity than its condition. Therefore, soil texture is discussed in the section "how to monitor".

Bulk density, expressed in mg/cm³, is a key indicator of soil compaction and overall soil health, influencing water infiltration, root development, and carbon stock estimates (Lee et al., 2009; Panagos et al., 2024; Vogt et al., 2015). It measures the dry mass of soil per unit volume and varies with management practices (Al-Shammary et al., 2018). Sampling methods include direct (core, clod, excavation) and indirect (radiation, regression) approaches; while indirect methods are more accurate, they are also costlier and require specialized skills (Vogt et al., 2015). Consistent fixed-depth sampling - ideally five samples per stand - is recommended to account for variability with depth (Cools & De Vos, 2010). In the SUPERB project, bulk density was measured using the core method at 0-5 cm (100 cm³ Kopecky ring), and an 18 mm auger for 5-15, 15-40, and 40-80 cm layers (FunDivEUROPE, 2011). Samples were oven-dried at 105 °C, weighed, and bulk density was calculated as dry mass divided by sample volume.

Additionally, **aggregate stability** is an important indicator for soil health because it is related to erodibility and soil-water dynamics (Rieke et al., 2022). Rieke et al., 2022 evaluated four methods for aggregate stability and concluded that all four methods were viable options. Considering cost-effectiveness, method accessibility, and time efficiency, the slaking test, adapted from the SLAKES smartphone image recognition software, offers a practical and scientifically robust approach for assessing aggregate stability in the field. This method is also preferred by the soil health institute (https://soilhealthinstitute.org/our-work/initiatives/slakes/).

2.2.2 Chemical properties

The chemical properties refer to the soil's composition and reactions. These properties determine how well soil can supply essential elements to plants and other soil organisms and buffer against pollutants. Here we propose to measure total soil carbon, total soil nitrogen and soil pH. Other properties that could be interesting to evaluate the soil's chemical condition are cation exchange capacity (CEC), as it reflects the soil's ability to retain and supply nutrients, electrical conductivity (EC), as it indicates soil salinity, and the soils status for specific nutrients that plants need to grow (e.g. NO3-, NH4+, P, K, base cation contents).

Measuring **soil carbon** helps to track how much carbon forests are sequestering and how environmental changes affect this role. Additionally, soil carbon is closely linked to soil fertility, structure, water retention and biological activity. Withing SUPERB, sampling for carbon was through the same method as for bulk density (FunDivEUROPE, 2011). Soil carbon occurs in both organic molecules and inorganic carbonates. Different analysing techniques are used depending on the type of carbon being measured. Methods for determining total carbon are through dry combustion or wet oxidation (Vogt et al., 2015). Within SUPERB, total carbon was analyzed. Soil samples were dried and crushed to obtain finely ground soil and analysed with the Flash 2000 Organic Elemental. This analysis works via dry combustion (T = 950 °C) followed by gas chromatography (Robertson, 1999). When carbonates were present in the soil, first hydrochloric acid was added to the soil sample to only obtain the soil organic carbon.

Soil **pH** is perhaps the most important factor in soil fertility and a critical indicator of soil quality, significantly influencing forest health and ecosystem functioning by affecting various biological and chemical processes. It also plays a crucial role in the activity and diversity of soil bacteria and fungi and is essential for the specific pH preferences of different tree species. (O'Neill et al., 2005; Singh et al., 2011; Thomas, 1996; Vogt et al., 2015). The soil pH was sampled using the same method as for soil carbon and pH (FunDivEUROPE, 2011). Regarding lab analysis, there is no standard procedure for measuring pH and can vary from laboratory to laboratory. pH can be measured using rapid field methods or more precise laboratory techniques: pH-H_2O and pH-KCL. pH-H_2O is determined by adding soil with water and measures only the free hydrogen ions (H^+) in the soil solution. It does not account for hydrogen ions that are attached to clay and organic matter. The pH-KCl is determined by mixing soil with a potassium chloride solution. The potassium ions (K^+) replace the hydrogen ions bound to clay and humus, so pH-KCl measures both the free and the exchangeable hydrogen ions in the soil (Van Ranst et al., 1999). Within SUPERB, pH-H_2O was measured on a 1g:10mL soil:liquid extract for the forest floor samples and a 1g:5mL soil:liquid extract for the mineral soil samples (Van Ranst et al., 1999). These ratios also apply when using the pH-KCl method with KCl 1M.

2.2.3 Biological properties

Soil biological properties consists of living organisms present in the soil, encompassing both microorganisms and macroorganisms, including plants and animals. This report focuses on soil microorganisms. Soil microbes break down the organic matter through catabolic processes. Additionally, they play a pivotal role in nutrient cycling, soil structure formation and overall soil fertility. Microorganisms are highly responsive to environmental changes, making them valuable indicators for assessing forest restoration. Various methods are available for determining soil microbial diversity, including culturing, microscopy, DNA-methods and image analysis (Vogt et al., 2015). In SUPERB, we report the potential catabolic activity/diversity and metabolic activity.

Assessing **catabolic microbial activity and diversity** is essential for understanding soil health. By evaluating potential catabolic activity, we can quantify the efficiency of microbial communities in mineralizing organic substrates, thereby releasing essential nutrients and contributing to the soil's nutrient pool (Vogt et al., 2015). Within SUPERB, we selected the Biolog EcoPlate™ method to measure this parameter (Gaublomme et al., 2006). Microorganisms inoculated onto different carbon sources leave a response pattern over a time (Biolog, 2023). To ensure accurate assessment, samples were collected in a sterile way by using disposable gloves, with all equipment sterilized using ethanol 90% and a gas burner. Samples were stored under cool conditions (7°C) and analyzed withing 14 days (FunDivEUROPE, 2013). In the lab, the fresh samples were being diluted and pipetted onto the Biolog EcoPlates™, containing 31 different carbon sources and 1 control in triplicates. The inoculated plates were placed in an incubator at 25°C for a period of 48 hours. The absorbance was measured after filling the ecoplates (day 0) using a VERSAmax microplate reader (OD590 nm) and on day 3 and 5. With the obtained data the average well color development and the Shannon diversity index can be expressed.

The metabolic activity is a sensitive indicator of many belowground processes and ecological interactions. Soil respiration is an indirect index for soil biological activity and can be used to assess microbial biomass (Vogt et al., 2015). Soil microorganisms respire carbon dioxide as a byproduct of metabolism while degrading organic matter and cycling nutrients (Rieke, Cappellazzi, et al., 2022). Within SUPERB, the microbial biomass was measured by incubating rewetted dried and sieved soil (10-15 gram) in a jar during 24 hours at 24°C (Comeau et al., 2023; Moebius-Clune, 2016; Soil health institute, 2022; Vogt et al., 2015). After 24 hours, CO_2 levels were measured using the LICOR 7810. The measurement was done by collecting the gas with a syringe and injecting the sample into the closed loop of the LICOR system (Comeau et al., 2023). The CO_2 levels were calculated by using the volume of the closed loop and the CO_2 concentration before and after the injection. A more cost-effective and simpler alternative for measuring carbon levels (compared to the LICOR) is the Checkpoint Dansensor.

Additionally, the **biomass of the fine roots** can also be determined. Fine roots are a key indicator of belowground productivity and nutrient uptake, as fine roots are primarily responsible for water and nutrient absorption. Measuring fine root biomass helps assess ecosystem functioning, soil-plant interactions, and the impact of environmental changes or restoration on root dynamics (Likulunga et al., 2022; Magalhães & Mamugy, 2020; Vogt et al., 2015). Within SUPERB, fine root sampling was conducted using the same methodology as for soil carbon (FunDivEUROPE, 2011). Because laboratory analysis of fine roots can be labor-intensive and time-consuming, we selected a less intensive sampling method to balance feasibility with data quality. For each sample, fine root picking was carried out for 5 minutes on the dried but unsieved soil, and fine root biomass was calculated by dividing the mass of the collected roots by the total volume of the dried sample (Likulunga et al., 2022; Magalhães & Mamugy, 2020).

2.3 How to restore

Multiple forest restoration strategies are studied within the framework of SUPERB, of which some barely impact soil health and others are explicitly targeted on soil health. A full explanatory list of forest restoration measures for every demonstration area can be found here: https://forest-restoration.eu/demo-areas/. Figure 2 provides an overview of the different restoration actions happening within SUPERB.

Figure 2: Overview of different restoration actions within SUPERB. Illustration by SUPERB (SUPERB, 2024).

The list of adopted restoration strategies within SUPERB is further specified and subsequently divided into three categories in the guidelines (Table 2): (i) afforestation/reforestation techniques, (ii) forest regeneration techniques and (iii) nursing techniques. Forest restoration measures that directly impact the soil are indicated by an * in table 2. This distinction is crucial as it recognizes that soil is both an integral and essential part of the forest ecosystem and a critical component that requires specific attention and management. Chapter 2.3.1 “Guidelines for restoration” discusses these same restoration techniques and their impacts on soil properties.

Table 2: List of restoration techniques in the guidelines divided into three categories: (i) afforestation/reforestation techniques, (ii) forest regeneration techniques and (iii) nursing techniques.

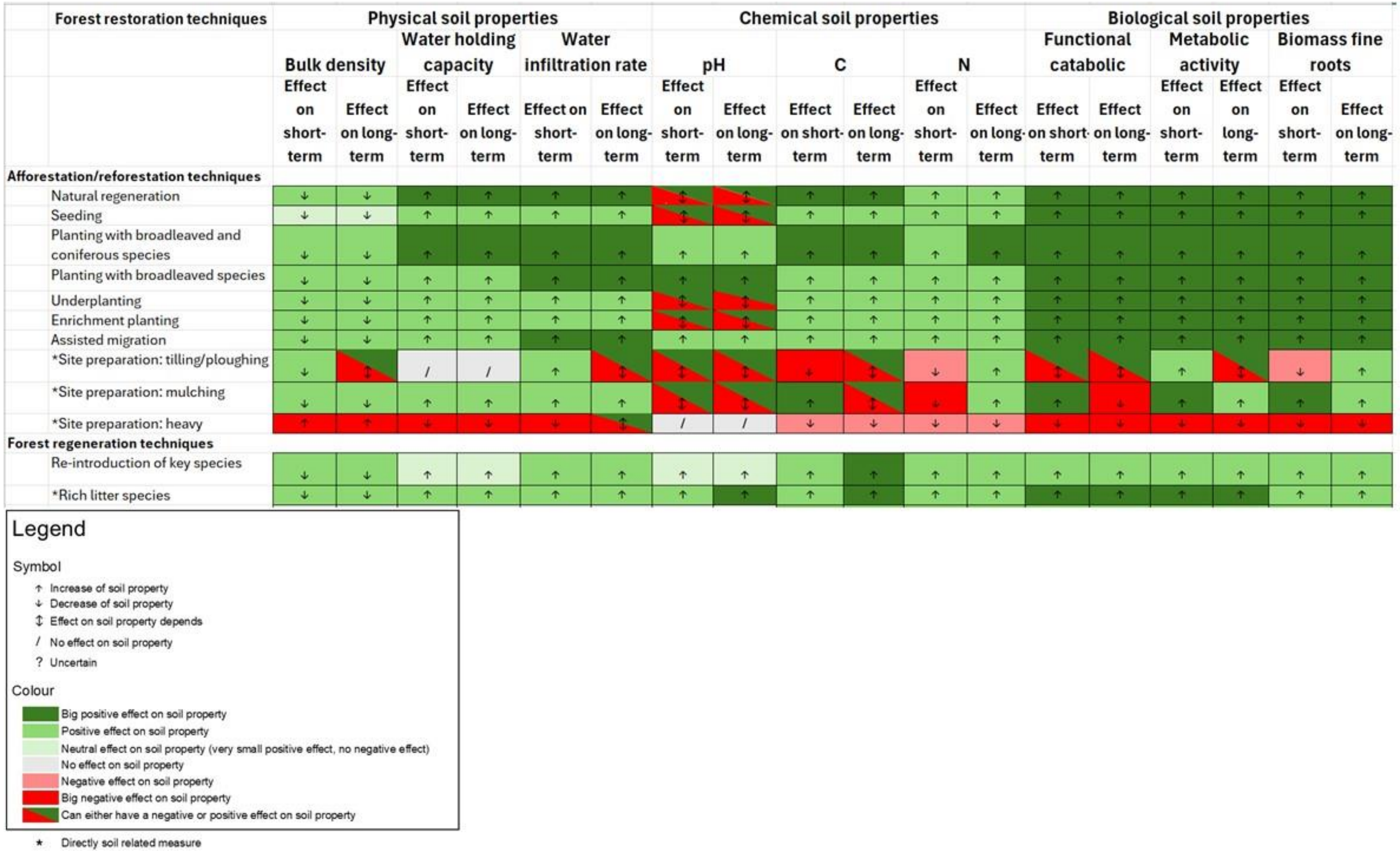
Afforestation/reforestation techniques	Forest regeneration techniques	Nursing techniques
Assisted migration	Clearcutting (followed by planting/natural regeneration)	Controlled burning
Enrichment planting	Coppice management	Control of invasive species
Natural regeneration	Creation of microhabitats	Fencing
Planting with broadleaved and coniferous species	Deadwood retention	Fire breaks
Planting with broadleaved species	*Dilution of soil contaminants	Pest and disease control
Seeding	*Fertilization	Pesticide application
*Site preparation: tilling/ploughing	Girdling	Protection of old growth remnants
*Site preparation: mulching	Harvesting individual trees	Protection of riparian forest
*Site preparation: heavy machinery	Harvesting group of trees (selection cut)	Veteranization of trees
Underplanting	*Inoculation of microorganisms	
	*Liming/rock dust application	
	*Organic amendments	
	Pruning	
	Re-introduction of key species	
	*Rich litter species	
	*Soil scarification	
	Thinning	

2.3.1 Guidelines for restoration

Figure 3 presents a partial overview of the restoration guidelines containing restoration techniques and their short- and long-term influence on different aspects of soil health (proxied by the proposed scalable indicators). The effects of the different techniques are categorized using symbols (arrows), indicating if the soil parameter in question increases or decreases, and colors, indicating the intensity of the effect on the soil parameter. This table serves as a practical reference for assessing the potential benefits and drawbacks of each approach in soil restoration and management.

When interpreting this table, several important disclaimers should be taken into account. First, previous land use plays a critical role in shaping the trajectory of soil recovery during restoration. Soil carbon, in particular, often reflects strong legacy effects from historical land use, which can persist for decades and influence the apparent success or failure of restoration interventions. Second, the way restoration measures are implemented significantly affects their impact. The quality and precision of management practices matter greatly. For example, when clearcutting is carried out using fixed skid trails, the extent of soil degradation is substantially reduced compared to more ad hoc approaches. Likewise, during soil preparation activities like ploughing, it is crucial to avoid excessive disturbance: ploughing too deeply can lead to long-term damage to soil structure and function. These nuances of implementation, which can determine the effectiveness of a restoration measure, are not captured in the table but are essential for accurate interpretation. Third, fire management practices such as controlled burning or the establishment of firebreaks can have localized negative effects on soil properties at the site of application. However, these interventions may provide important protective benefits at the landscape level by reducing the risk and severity of uncontrolled wildfires. As such, while their immediate impact on soil may appear detrimental, their broader role in preserving forest integrity must also be considered. Finally, these guidelines represent an initial expert-based assessment of the potential effects of forest restoration measures on soil properties. They are mostly informed by interviews with specialists, our own fieldwork and a limited body of scientific literature. Due to limited availability of these peer-reviewed data, some evaluations remain qualitative or preliminary. As such, the guidelines should not be interpreted as definitive, but rather as a starting point for discussion and refinement. To advance this process, we propose organizing a stakeholder and expert workshop within the SUPERB framework, with the aim of validating and enriching these initial findings. The full table can be found in the excel file Forest Soil Restoration Guidelines_table.xlsx.

Using two demo cases from SUPERB we will illustrate the use of the table.



Forest restoration techniques	Physical soil properties: Bulk density – Effect on short-term	Bulk density – Effect on long-term	Water holding capacity – Effect on short-term	Water holding capacity – Effect on long-term	Water infiltration rate – Effect on short-term	Water infiltration rate – Effect on long-term	Chemical soil properties: pH – Effect on short-term	pH – Effect on long-term	C – Effect on short-term	C – Effect on long-term	N – Effect on short-term	N – Effect on long-term	Biological soil properties: Functional catabolic – Effect on short-term	Functional catabolic – Effect on long-term	Metabolic activity – Effect on short-term	Metabolic activity – Effect on long-term	Biomass fine roots – Effect on short-term	Biomass fine roots – Effect on long-term
Afforestation/reforestation techniques																		
Natural regeneration	↓	↓	↑	↑	↑	↑	↕	↕	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Seeding	↓	↓	↑	↑	↑	↑	↕	↕	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Planting with broadleaved and coniferous species	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Planting with broadleaved species	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Underplanting	↓	↓	↑	↑	↑	↑	↕	↕	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Enrichment planting	↓	↓	↑	↑	↑	↑	↕	↕	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Assisted migration	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
*Site preparation: tilling/ploughing	↓	↕	/	/	↑	↕	↕	↕	↓	↕	↓	↑	↕	↕	↑	↕	↓	↑
*Site preparation: mulching	↓	↓	↑	↑	↑	↑	↕	↕	↑	↕	↓	↑	↑	↓	↑	↑	↑	↑
*Site preparation: heavy	↑	↑	↓	↓	↓	↕	/	/	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
Forest regeneration techniques																		
Re-introduction of key species	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
*Rich litter species	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑

Figure 3: Partially overview of the table with guidelines containing forest restoration measures and their impact on different soil parameters. The legend explains how to interpret the colours and symbols. Colours indicate a positive or negative effect, while the arrows indicate if there is an increase or decrease of the soil properties.

Case 1: Rich litter tree species planting in the Netherlands

In the Dutch demo site of SUPERB (de Graaf & Raats, 2024), pine plantations are characterized by low vitality and diversity as a consequence of acidified sandy soils and nutrient imbalances. The acidification is a consequence of centuries of heathland management, followed by more recent atmospheric sulphur and nitrogen depositions. The restoration measures that are taken by the Dutch partner include underplanting with broadleaved rich litter species, fertilization and liming/rock dust application. All of these measures are targeted on counteracting soil acidification and thus have a positive effect on soil pH.

Figure 4 shows an overview of the restoration measures applied in the Dutch demo area. **Overall,** these restoration measures pose a positive influence on the different soil properties (green colour) on the short- and long-term. All techniques lead to a decrease (arrow down) in bulk density and an increase (arrow up) of all other properties. The effects of **enrichment planting** and **underplanting** on soil pH can vary (red/green colour and double arrow) depending on the functional traits of the introduced species. In the Dutch demo area, where soils are already affected by acidification, the selected species for underplanting and enrichment are expected to contribute to an increase in soil pH due to their less acidifying litter inputs and associated biogeochemical processes. The colour intensity shows how strong the impact of each restoration measure is, e.g. liming/rock dust application will impact bulk density less compared to enrichment planting.

Forest restoration techniques	Physical soil properties						Chemical soil properties						Biological soil properties					
	Bulk density		Water holding capacity		Water infiltration rate		pH		C		N		Functional catabolic diversity		Metabolic activity		Biomass fine roots	
	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term
Afforestation/reforestation techniques																		
Planting with broadleaved species	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Underplanting	↓	↓	↑	↑	↑	↑	↕	↕	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Enrichment planting	↓	↓	↑	↑	↑	↑	↕	↕	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Forest regeneration techniques																		
*Rich litter species	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
*Fertilization	↓	↓	/	/	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
*Liming/rock dust application	↓	↓	/	/	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑

Legend

Symbol

↑ Increase of soil property
↓ Decrease of soil property
↕ Effect on soil property depends
/ No effect on soil property
? Uncertain

Colour

Big positive effect on soil property
Positive effect on soil property
Neutral effect on soil property (very small positive effect, no negative effect)
No effect on soil property
Negative effect on soil property
Big negative effect on soil property
Can either have a negative or positive effect on soil property

* Directly soil related measure

Figure 4: Printscreen of restoration guidelines for relevant strategies for the Dutch demo area and their impact on soil properties.

Case 2: Converting spruce monocultures facing windthrow to continuous cover forestry in Scotland, UK.

In the the UK demo area (Locatelli et al., 2024), large areas in Queen Elizabeth Forest Park have historically been dominated by Sitka spruce monocultures. The predominance of waterlogged soils with gleyic properties makes these stands highly susceptibility to wind damage. Current restoration efforts aim to deliver a wider range of ecosystem services by introducing Continuous Cover Forests (CCF) in spruce stands with thinning and future retention trees.

Figure 5 shows an overview of the restoration measures applied in the Scottish demo area. Overall, site preparations through **tilling/ploughing** do not have an optimal influence on all soil properties on the short-term (red colour) by disrupting soil structure, breaking up fungal hyphae, and altering microbial habitat conditions. On the long-term, there can be a positive or negative evolution depending on the context. pH can be both on the short-and long-term positively or negatively influenced. For example, localized acidification can be neutralized by mixing soil layers; and enhanced aeration can promote microbial processes. However, tillage can also accelerate the oxidation of soil organic matter, producing acidic by-products. Bulk density typically decreases immediately following ploughing due to the loosening and aeration of the topsoil, but again can go in both ways on the long-term. The metabolic activity will be positively influenced on the short-term, while diversity can go both ways. **Planting with broadleaved and coniferous species and thinning** overall has a positive influence (green colour) on all soil parameters with a decrease for bulk density and an increase for all other parameters.

Forest restoration techniques	Physical soil properties						Chemical soil properties						Biological soil properties					
	Bulk density		Water holding capacity		Water infiltration rate		pH		C		N		Functional catabolic		Metabolic activity		Biomass fine roots	
	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term	Effect on short-term	Effect on long-term
Afforestation/reforestation techniques																		
Planting with broadleaved and coniferous species	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
*Site preparation: tilling/ploughing	↓	↕	/	/	↑	↕	↕	↕	↓	↕	↓	↑	↕	↕	↑	↕	↓	↑
Forest regeneration techniques																		
Thinning	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑

Legend

Symbol

- ↑ Increase of soil property
- ↓ Decrease of soil property
- ↕ Effect on soil property depends
- / No effect on soil property
- ? Uncertain

Colour

- Big positive effect on soil property
- Positive effect on soil property
- Neutral effect on soil property (very small positive effect, no negative effect)
- No effect on soil property
- Negative effect on soil property
- Big negative effect on soil property
- Can either have a negative or positive effect on soil property

* Directly soil related measure

Figure 5: Printscreen of restoration guidelines for relevant strategies for the demo area in Scotland, UK, and their impact on soil properties.

2.4 How to monitor

2.4.1 Establish a baseline by mapping soil capability

In order to effectively monitor the impact and success of restoration, it is important to establish a **baseline** that provides a detailed inventory of the existing forest conditions and allows to see if forest restoration is effective. For this, using the BACI design (Before-After-Control-Impact) is a good strategy, which is a scientific method to assess the effects of an intervention by comparing conditions before and after the event. The same is true for the soil compartment, restoration cannot be monitored properly without **mapping the soil capability** (see chapter 1.4) as it provides critical insights into the intrinsic potential of a site. Accurate mapping allows practitioners to identify areas of degradation, prioritize sites for intervention, monitor restoration progress, and assess ecosystem recovery over time. Maps of underlying geology and soil types are particularly important, as they provide essential baseline information that influences restoration strategies and long-term forest development. Comparing these maps to relevant literature, such as journal articles on forest or soil conditions in the region or historical land use studies, further strengthens site interpretations by connecting field observations with broader regional patterns and historical context. High-resolution spatial data, combined with advances in remote sensing, geographic information systems (GIS), and field surveys, enables a precise understanding of landscape conditions both before and after restoration interventions. Modern technologies such as drone-based aerial surveys, LiDAR (Light Detection and Ranging), and satellite imagery (e.g., Sentinel) have vastly improved the ability to map forest structure, canopy cover, species composition, and soil properties across large and often inaccessible areas. Field-based site observations however, remain crucial and should follow standardized methods for soil description, such as those outlined in national or international soil survey guidelines (e.g., FAO Guidelines for Soil Description: https://www.fao.org/4/a0541e/a0541e.pdf). These standardized descriptions can be integrated with GIS to build comprehensive spatial databases that support targeted, evidence-based forest restoration planning.

Soil texture is an important soil property to evaluate in this context. Soil texture serves as a fundamental, non-modifiable property that underpins many soil functions and processes, yet it cannot be altered through restoration efforts. It refers to the relative proportions of sand, silt, and clay particles and plays a crucial role in shaping the physical and chemical properties of soil. The texture will be determining for the total amount and distribution of pore space, which affects water retention, drainage, and aeration, making soil texture a key factor for plant growth (Eshel et al., 2004; van Es et al., 2017). Understanding soil texture variability is essential for developing site-specific management strategies. It is also a key characteristic that influences the carbon cycle in forest - affecting both tree growth, soil organic matter retention and microbial activity- and can therefore modulate the impacts of climate change (Gómez-Guerrero & Doane, 2018). Within SUPERB, soil texture was determined using a Beckman-Coulter LS 13 320. To do this, dry and sieved soil samples were pretreated with 10% hydrochloric acid and 35% hydrogen peroxide to remove carbonates and organic components. To ensure proper dispersion of clay particles, ultrasonication was applied. During analysis, an obscuration level between 19% and 22% was maintained for optimal accuracy. Particle size classes were defined as follows: clay 0.04 µm-8 µm, silt 8 µm-58µm, and sand 58 µm-2000 µm (Eshel et al., 2004). When working in the field and immediate information about soil texture is needed, the hand texture method offers a quick and practical assessment. This technique allows you to estimate soil texture by feeling the soil's consistency, grittiness, and stickiness. This method ideally should be done by experienced people (Vogt et al., 2015).

In addition to mapping capability, it is important to clearly understand the **underlying degradation problems** affecting the forest sites. This includes identifying the causes of degradation, assessing current ecological conditions and recognizing site-specific limitations or threats. Further, it is important to establish clear **restoration targets**. Restoration targets define the desired outcomes of a restoration project and provide a measurable framework for success. They should be based on ecological reference conditions, site potential, and broader landscape objectives. Clear targets guide the selection of appropriate species, management actions, and monitoring indicators. They also help align stakeholder expectations and enable adaptive management if conditions change.

2.4.2 Monitor soil condition before and after restoration using scalable indicators

Post-restoration mapping enables the tracking of vegetation regrowth, soil recovery, carbon sequestration, and biodiversity returns over time, providing evidence of restoration success or highlighting areas needing additional support. For the follow up of soil conditions we recommend to evaluate the properties proposed in table 1of section "What to restore". The actual monitoring guidelines presented in table 3 outline the scalable indicators for monitoring, including recommended sampling frequency, sampling time, sampling and analysing methodologies and costs.

2.4.3 Guidelines for monitoring

Table 3 provides an overview of scalable indicators for monitoring along with their sampling and analytical methods (same sampling and analysis methods as described in chapter 2.2). Further information regarding this table can be found in the guidelines for developing MRV reports (Measuring, Reporting and Verification of Forest Restoration), published by SUPERB.

Table 3: Scalable indicators and corresponding sampling and analysing methodologies.

	Carbon (%)	Nitrogen (%)	pH	Bulk density (g/cm³)	Biomass fine roots (g/cm³)	Functional catabolic diversity	Metabolic activity (ppm)
Soil property	Chemical	Chemical	Chemical	Physical	Biological	Biological	Biological
Importance	Soil organic matter	Plant growth	Nutrient availability, microbial communities and decomposition rate	It reflects soil compaction, influencing multiple soil functions	Nutrient and water uptake	Microbial functional capacity	Living component of soil organic matter
Sampling before every intervention?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sampling after every intervention?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Long-term sampling frequency	Every 10 years	Every 10 years	Every 10 years	Every 5 years	Every 5 years	Every 5 years	Every 5 years
Sampling depths	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm	OL+OF+OH 0-5 cm 5-15 cm
Sampling time (3 augerings per site) *	~1 hour					~30 minutes	
Sampling method	Sampling for soil carbon stocks	Sampling for soil carbon stocks	Sampling for soil carbon stocks	Manual on methods for harmonized sampling, assessment, monitoring and analysis	Sampling for soil carbon stocks	Sampling for microorganisms	Sampling for microorganisms
Analysed depths	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm 15-40 cm 40-80 cm	OL+OF+OH 0-5 cm 5-15 cm	OL+OF+OH 0-5 cm 5-15 cm	0-5 cm

Analysing method	Standard Soil Methods for Long-Term Ecological research	Standard Soil Methods for Long-Term Ecological research	Manual for the Soil Chemistry and Fertility Laboratory	Manual on methods for harmonized sampling, assessment, monitoring and analysis	Likulunga et al., 2022 Magalhães et al., 2020	An indicator for Microbial Biodiversity in Forest Soils (p115-117)	Potential Carbon Mineralization
Cost per sample (per fixed depth)	100 euros	100 euros	100 euros	50 euros	200 euros	200 euros	150 euros

* The time needed for soil sampling is influenced by the physical state of the soil, including factors such as stoniness, moisture conditions (e.g., dry or wet soils), and soil texture, all of which can affect sampling feasibility.

3. Information on documents in the Annex

As already described in chapter 2.3.1, we provide a table containing restoration techniques and their short- and long-term influence on different aspects of soil health. The effects of the different techniques are categorized using symbols (arrows), indicating if the soil parameter in question increases or decreases, and colors, indicating the intensity of the effect on the soil parameter. This table serves as a practical reference for assessing the potential benefits and drawbacks of each approach in soil restoration and management. The full table can be found in the excel file Forest Soil Restoration Guidelines_table.xlsx.

4. Conclusion

Forests and forest soils are critical components of terrestrial ecosystems, delivering a wide range of ecosystem services, including carbon sequestration, climate regulation, nutrient cycling, and water filtration. Therefore, their conservation should be prioritized wherever feasible to maintain ecological function and long-term sustainability. In cases where conservation is no longer viable due to anthropogenic disturbance or natural degradation, ecological restoration becomes necessary. Restoration efforts should adopt a holistic approach that promotes the recovery of soil health, including soil physical, chemical, and biological properties, while recognizing the intrinsic interconnection between forest and soil restoration. To effectively guide restoration, it is essential to assess both the condition and the capability of soils through spatial mapping and site-specific diagnostics. This enables the selection of appropriate restoration strategies that align with soil constraints and potential. Furthermore, soil capability mapping can inform realistic expectations for ecosystem service recovery. Restoration itself can consist of multiple techniques and interventions, which are being summarized in this report along with their impact on different soil parameters. This practical tool allows selecting context-appropriate interventions that effectively support soil health recovery and ecosystem resilience. Monitoring is a critical component to guide and evaluate restoration success by using scalable indicators that are cost-effective, time-efficient and applicable across spatial scales. These indicators enable cross-site comparisons and long-term assessments. Mapping soil capability and condition prior to restoration allows for the identification of site-specific limitations and potentials. Monitoring should begin with a pre-restoration baseline to establish reference conditions and guide indicator selection. Additionally, Identifying degradation problems is an important step in the pre-monitoring phase. Post-restoration monitoring must be structured, consistent, and longitudinal, capturing short- and long-term soil responses. The use of scalable indicators facilitates tracking of soil recovery across heterogeneous landscapes, improving comparability and policy relevance.

Adaptive management relies on such monitoring to evaluate progress and refine restoration strategies. Overall, integrated soil-focused restoration strategies are essential for rebuilding degraded forest ecosystems and securing the services they provide.

5. Resources

- SUPERB Project poster
- SUPERB Project flyer
- SUPERB restoration Workplan: Southern Netherlands
- SUPERB restoration Workplan: Queen Elizabeth Forest Park, Scotland

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