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REECOL Ecological rehabilitation and long term monitoring of post mining areas

Deliverable 5.1

Definition of soil function monitoring toolbox

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1. Introduction

Coal mining became increasingly important during the industrial revolution in the 19th and 20th centuries when the demand for fossil fuel to produce electricity, heat buildings and power steam engines increased. There are around 50 mining regions across Europe, the most active being in Germany and Poland. Although coal extraction has decreased by about 3% each year over the last decade, in 2020 around 480 million tons were extracted and the coal industry was estimated to employ up to 185 000 people. European institutions aim to exit coal and reduce coal-fuelled power plants by two thirds before 2030 and to reduce emissions by 55% until 2030. It is planned that in 2050 Europe will become climate neutral. This is one of the crucial aims of the European Union that is presented in the European Green Deal.

In this framework, and in the light of the European Green Deal objectives and global EU aims to achieve a successful and just transition towards a sustainable future with a climate neutral economy, and in line with RFCS objectives to assist coal EU regions the most affected by the transition in achieving these objectives, the overall goal of REECOL is to build on existing knowledge and experience of post-mining rehabilitation approaches to propose a procedure for accompanying the transition of coal mining areas while considering ecosystem rehabilitation and monitoring, future intended land uses and the affordability of the solutions.

Objective 3 of REECOL is to develop and test tools for efficient short and long term monitoring of ecosystem rehabilitation, suited for various post-mining rehabilitation approaches. This objective is targeted in WP5 of which this report is the first deliverable. In order to improve ecological rehabilitation we need to identify tools suitable for in situ short and long term monitoring. These tools allow the monitoring of some key indicators that aim to quantify rehabilitation success and associated ecological benefits. Short term monitoring indicators will typically be field grounded (e.g. botanical survey or soil analyses to access ecological functions) while long term indicators will be remote sensing based (e.g. vegetation covering, normalized difference vegetation index). Long term monitoring solutions will be essential for sustainability measurements, they focus on the use of satellite imagery and remote sensing data and will be tested in the case study areas. The satellite and unmanned aerial vehicle (UAV) data will be used for monitoring results of reclamation activities and observing undesired processes on land with high redevelopment potentials (spreading of invasive species and succession of woody vegetation).

The ecological restoration of mines presents a complex challenge involving various factors such as ecology, land use, and landscape. The goals and methods for restoring abandoned mines are gradually shifting from a focus solely on ecological restoration to promoting sustainable regional socioeconomic development. Advancements in mine ecological restoration technology have led to an expansion of reclamation approaches and a redefinition of reclamation objectives, demanding a more comprehensive evaluation of mine reclamation effectiveness. This evaluation must consider the long-term and large-scale nature of mine ecological restoration, while also encompassing the diverse methods and goals employed in the reclamation and restoration of abandoned mines. Assessments of sample sites offer valuable data on local spatial variations but fall short of providing a holistic global evaluation due to limitations imposed by spatial and temporal constraints. At a broader scale, remote sensing technology has emerged as a crucial tool for conducting comprehensive evaluations of mine management effectiveness, thanks to its ability to offer multi-temporal, high spatial coverage data that is easily accessible. Consequently, conducting a comprehensive evaluation that considers the unique attributes of ecological restoration involving diverse methods and objectives becomes even more challenging (Holl, 2020).

There is a growing need for the integration of machine learning methods in the evaluation of mine reclamation effectiveness and the broader field of ecological restoration of mines. Machine learning techniques can play a crucial role in enhancing the accuracy, efficiency, and scope of evaluations by utilizing complex algorithms to analyze large datasets and identify patterns that may not be apparent through traditional methods (Mentis, 2020).

In the context of mine management effectiveness, machine learning algorithms can be used to process and analyze vast amounts of data collected through remote sensing technologies, providing valuable insights into the ecological status of abandoned mines. These algorithms can help in identifying trends, anomalies, and correlations within the data that can inform decision-making processes related to mine restoration strategies and monitoring efforts. Furthermore, machine learning models can be trained to predict the outcomes of different restoration approaches based on historical data, enabling stakeholders to optimize resource allocation and prioritize interventions that are most likely to yield positive results. By using machine learning, researchers can gain a deeper understanding of the

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complex interactions between ecological factors and reclamation effectiveness, leading to more informed and data-driven decisions in the field of mine ecological restoration. Overall, the integration of machine learning methods holds significant promise in advancing the field of mine restoration by enabling more sophisticated analyses, enhancing predictive capabilities, and supporting the decision-making processes (BANDYOPADHYAY & MAITI, 2021).

Self-organizing maps (SOMs), are a type of artificial neural network that can be used for dimensionality reduction, clustering, and visualization of high-dimensional data. SOMs are particularly useful for analyzing complex and nonlinear relationships within datasets, making them a valuable tool in various fields, including data mining, pattern recognition, and image processing. In the context of ecological restoration of mines, self-organizing maps can be utilized to analyze and visualize multi-dimensional data collected from remote sensing technologies, such as satellite imagery. By applying SOMs to this data spatial patterns, trends, and clusters can be identified that may not be readily clear through traditional methods. SOMs can help in organizing and grouping spatial data as well as for gap filling based on similarity, allowing for the identification of distinct ecological zones within a mine site. This information can be used to inform decision-making processes related to mine restoration strategies, resource allocation, and monitoring efforts. In summary, self-organizing maps offer a powerful and versatile tool for analyzing spatial data in the context of mine ecological restoration, enabling researchers and practitioners to uncover valuable insights, identify patterns, and make data-driven decisions to support effective restoration efforts (BANDYOPADHYAY & MAITI, 2021; ZHU ET AL., 2020).

Results will provide a selection of tools and tested methodologies for site managers and contribute to defining criteria for the certification method proposed by REECOL.

The present report presents the ecological function approach chosen to evaluate ecosystem rehabilitation and gives an overview of the parameters identified by REECOL partners for monitoring ecosystem rehabilitation for each of these functions.

2. Methodology

Depending on the desired new use of a site, ecological rehabilitation using nature-based solutions (NBS) will aim to reach the expected ecological services (i.e provisional, regulating or cultural). These services are based on “support services” or ecosystem functions which are all the natural processes inherent in an ecosystem, such as organic matter mineralization, water cycling, nutrient provision to plants. Each of the functions of an ecosystem can be characterised by one or more chemical, physical or biological processes, which can generate ecosystem services. In rehabilitation, soils play a first order role. Nine ecological functions have been identified that are inherent to soils (BLANCHART ET AL., 2019; EFESE). Processes inherent to soil functions are the result of interactions between abiotic and biotic components of soil. Their evaluation can be obtained by measuring physico-chemical and biological parameters (ex: nitrogen, carbon, water holding capacity, microbial biomass, carbon mineralization, etc.). Some of these parameters are direct indicators while others, such as soil texture, are components that will influence these processes. More and more work is also moving towards the evaluation of functions by evaluating groups of parameters (BLANCHART ET AL., 2019). Many physico-chemical parameters are known to reflect soil quality from an agronomic point of view (BASTIDA ET AL., 2008) and the review by Bünemann et al. (2018) showed their prevalence in function measurement studies, although biological indicators can also provide significant information on soil functioning. Indeed, biological indicators are more sensitive to short term disturbances (BASTIDA ET AL. 2008). Various recent or ongoing studies have identified known indicators, biotic and abiotic, of soil functions (BAPTIST ET AL., 2018). Currently, soil monitoring at European level is based on physico-chemical data such as the RMQS (Soil Quality Measurement Network) (MORVAN ET AL., 2008). In recent years, however, several projects have focused on the identification of sensitive biological indicators and from July 2023 discussions have been reopened for a European Soil Framework Directive.

Soils contain a great abundance and diversity of microorganisms which are key players in many ecosystem functions and services, and therefore in soil quality (BRACKIN ET AL., 2017). Information on soil biodiversity as well as on the biological activity of its micro-organisms would provide a more precise view of the state of soil functions and services because they influence important processes specific to this ecosystem (VINCENT ET AL., 2018; BRACKIN ET AL., 2017). Remote sensing is the process of measuring reflected radiation at a distance (typically from satellite or aircraft). Remote sensing technology allows for detecting and monitoring the physical characteristics of large areas. The remote sensing data are used for soils, forestry, agriculture, urban and water research (PANDEY ET AL., 2020;

PIERZCHAŁA, 2020) In the term of reclamation of degraded areas remote technologies are used mostly for identification of spatio-temporal changes in land cover forms. The health state of vegetation is then assessed based on normalized difference vegetation index (NDVI), normalized difference moisture index (NDMI), enhanced vegetation index (EVI) and radar vegetation index (RVI) indicators that have been delivered by U.S. Geological Survey (Landsat 5 and 8 satellite images) (BUCZYŃSKA 2020).

Many (bio)indicators or parameters of soil and above ground ecosystems are available in the literature and reflect their functioning. Many efforts have been invested in soil fertility and agricultural soils. However, to date, very few approaches are available for measuring derelict soil and their re-functionalization during ecological rehabilitation, whether on the short or the long term. WP5 is dedicated to defining the toolbox for monitoring the short and long-term rehabilitation of mining areas in relation to the proposed future uses as well as providing the means for data interpretation. Indeed, during a post mining rehabilitation scheme, site managers need to rely on a robust set of indicators to make a useful evaluation of the state and progress of soil ecological functions such as water retention, carbon and organic matter dynamics, risk of pollutant transfer, availability of nutrients for plant growth or the potential of the site as a biodiversity reservoir.

Based on existing knowledge this first deliverable of WP5 of REECOL aims to define a toolbox of methods and (bio)indicators to measure key ecological functions and processes that reflect the degree and nature of ecosystem degradation and that are tailored to monitor the rehabilitation scenarios.

3. Soil ecological functions and different scales

The parameters for soil description, whether they relate to pedology, fertility, or soil biodiversity, act as indirect regulatory variables for soil functions. Indeed, while they do not directly constitute the processes supporting ecological functions, these parameters define the soil's potential and influence the ecological processes that underpin these functions. Therefore, assessing these parameters is crucial for establishing rehabilitation strategies, identifying action levers, and measuring the success of rehabilitation efforts.

Presently, the concepts of soil health and soil quality intertwined with soil function description give both a static assessment of soil (i.e parameters that change only on the long term) versus a more dynamic assessment of soil which involves soil processes and biological activity. Moreover, in the framework of REECOL, links between small-scale soil measurements (i.e carried out on collected soil samples) and large-scale measurements using remote sensing and satellite images are aimed to be made to enable long-term monitoring of large areas in remote regions.

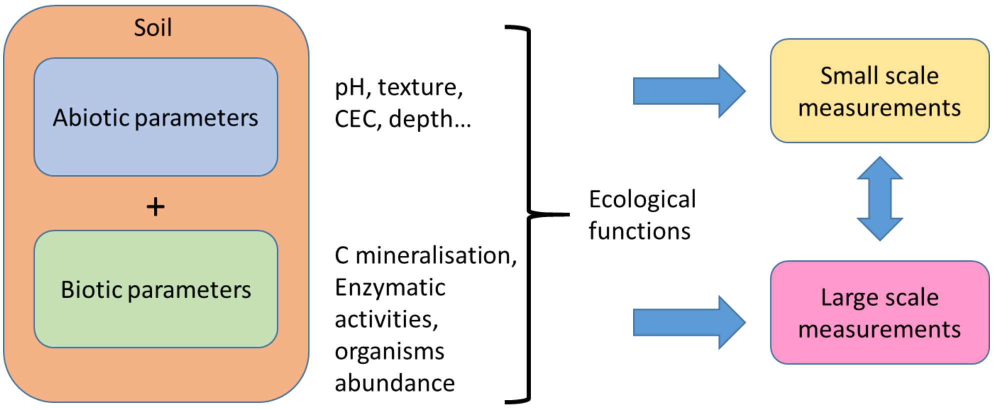

Figure 1. Conceptual framework for the assessment of soil ecological functions

Here after this report first presents parameters for assessing soil pedological parameters, followed by small scale measurements of the 6 ecological functions described below and finally the large scale measurements identified by REECOL partners.

Habitat and biodiversity regulation: The soil function "Habitat and Biodiversity Regulation" refers to the role of soil in providing a living space for a wide range of organisms, thereby supporting biodiversity. Soil biodiversity is

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also crucial for the survival of numerous microorganisms, invertebrates, and small mammals, each playing a vital role in various ecological processes.

Nutrient capture for soil organisms and plants: The soil function “Nutrient Capture for Soil Organisms and Plants" refers to the soil's capacity to retain and provide essential nutrients for the growth and sustenance of both soil organisms and plants. This function is vital for ecosystem productivity and health. Soil acts as a reservoir for nutrients such as nitrogen, phosphorus, potassium, and numerous trace elements critical for plant growth. This function is fundamental for supporting diverse ecosystems by enabling the growth of a wide range of plant species, which in turn support a variety of animal life through the provision of food.

Organic matter storage and cycling: The soil function "Organic Matter Storage and Cycling" refers to the soil's ability to accumulate, break down, and recycle organic materials, such as plant residues, animal remains, and microbial biomass. This function is critical for maintaining soil fertility, structure, and overall ecosystem health.

Soil Structure maintenance for plants: The soil function "Soil Structure Maintenance for Plants" refers to the soil's ability to maintain a physical framework that supports plant life by providing stability, proper aeration, and moisture conditions. This function is crucial for the growth and health of plants and affects everything from seed germination to root development and the overall productivity of ecosystems.

Water retention and infiltration: The soil function "Water Retention and Infiltration" refers to the soil's ability to absorb, hold, and release water, which is crucial for sustaining plant life, regulating surface water flow, and maintaining ecosystem health.

Pollutant attenuation and degradation: The soil function "Pollutant Attenuation and Degradation" refers to the soil’s ability to reduce the concentration and/or toxicity of pollutants through various physical, chemical, and biological processes. This function is crucial for protecting groundwater quality, maintaining ecosystem health, and supporting human health by mitigating the impacts of environmental contaminants.

4. In situ (Small scale) function assessment

Mining sites have a significant impact, potentially affecting vast areas. Mining activities can lead to soil degradation, thereby disrupting the ecological functions of the soil. The rehabilitation of these damaged sites is a complex process that, through a parcel-based approach, allows for the adaptation of rehabilitation techniques to the specific conditions of each portion of land, thereby optimizing the chances of ecological recovery and sustainable reclamation of soils degraded by mining activities.

Thus, small-scale evaluation of soil ecological functions is essential to understand and assess the rehabilitation of these sites. This evaluation relies on a set of varied measurements that identify and quantify the parameters influencing the soil's capacity to fulfil its ecological functions. These measurements are divided into two main categories: abiotic parameters and biotic parameters. Abiotic parameters include elements such as soil texture, pH, organic matter content, and water retention capacity, which can be measured directly on the parcel or via samples analysed in the laboratory. Biotic parameters, on the other hand, encompass microbial diversity, root abundance, and enzymatic activity, among others, often requiring samples followed by detailed laboratory analyses for precise evaluation. These two types of measurements provide complementary and indispensable information for a comprehensive understanding of soil ecological functions at the parcel scale.

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4.1. Abiotic parameters

Table 1. Link between abiotic parameters and ecological functions

Parameter	Habitat and biodiversity regulation	Nutrient capture for soil organisms and plants	Organic matter storage and cycling	Soil structure maintenance for plants	Water retention and infiltration	Pollutant attenuation and degradation
Texture	✓	✓		✓	✓	✓
Porosity	✓			✓	✓	
Compaction	✓			✓	✓	
Soil depth	✓			✓	✓	
Aggregate stability	✓			✓	✓	
Soil density	✓			✓	✓	
Soil water holding capacity	✓			✓	✓	
Soil water availability					✓	
Soil water permeability					✓	
Soil organic matter	✓	✓	✓	✓	✓	✓
Soil organic carbon	✓	✓	✓		✓	✓
Thermolabile carbon		✓	✓			
Thermoresistant carbon		✓	✓			
Soil inorganic carbon		✓	✓			
pH water	✓	✓		✓		✓
Total nitrogen		✓	✓			
Mineral Nitrogen	✓	✓	✓	✓		
Total phosphorus		✓	✓			
Phosphorus availability	✓	✓	✓	✓		✓
Cationic exchangeable capacity	✓	✓		✓		✓
Carbon / Nitrogen ratio	✓	✓	✓	✓		
Contaminant concentrations (total and extractable)	✓	✓	✓		✓	✓

4.1.1. Texture

Definition

Soil texture represents the relative content of particles of various sizes including sand (2mm-200µm), silt (200µm - 50µm) and clay (<50µm). The USDA textural classes (IUSS WORKING GROUP WRB, 2022) of soil divide soils into 12 main classes depending on this ratio, from sandy soils (coarse texture) to clayey soils (fine texture) (Fig. N.2)

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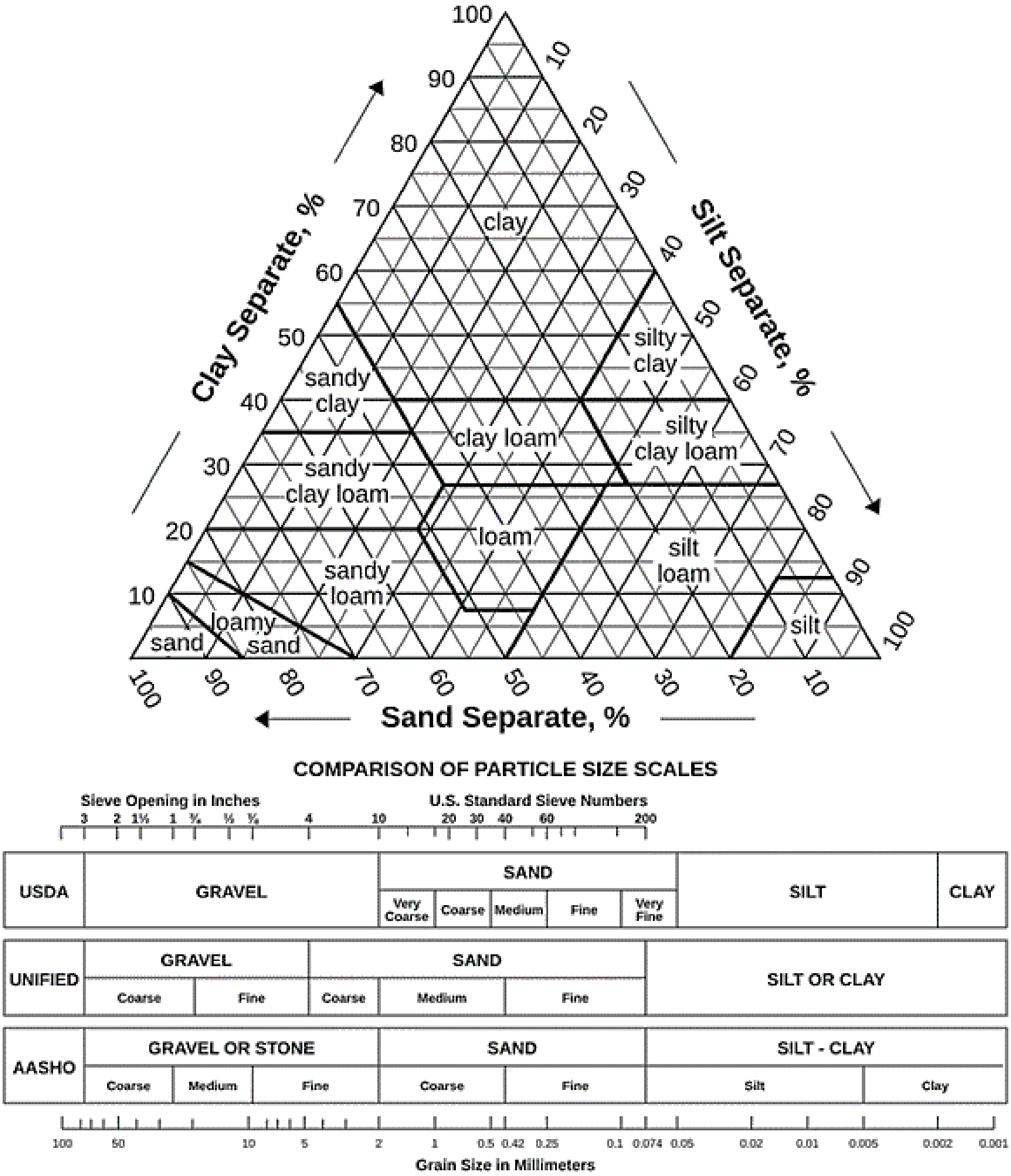

Figure 2. Triangle of soil texture representing the 12 main texture classes and particle size as defined by the USDA

How to assess

Several methods exist (IUSS Working group WRB, 2022) to calculate the sand-silt-clay ratio corresponding to a soil texture (by feeling directly in the field, by sieving, by hyrometer method or by laser diffraction), but the sieving method on the fine fraction of the soil (<2mm) remains the most largely used. This method consists in sieving a soil sample through 3 different sieves of 2mm, 200µm and 50µm to determine the ratio of sand-silt-clay.

Application context

As soil texture does not vary significantly over time, an initial evaluation before and after rehabilitation can be performed to evaluate the initial texture of the plot as well as the impact of the rehabilitation.

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Link with ecological soil functions

Texture is an important soil parameter as it influences soil air content as well as soil water retention capacity and water availability for plants, depending on the sand-silt-clay ratio. This ratio also has an impact on hydrogeomorphic parameters such as soil retractation capacity.

4.1.2. Porosity

Definition

Soil porosity is the ratio of nonsolid volume to the total volume of soil. Soil porosity is important to conduct water, air, and nutrients into the soil (Indoria et al., 2020; Ramesh et al., 2019).

How to assess

The measurement of soil porosity is standardised by EN ISO 11508:2017 norm.

Application context

Soil porosity changes over time due to various natural and anthropogenic factors. Natural processes such as biological activity, root growth, and freeze-thaw cycles constantly alter the soil structure, thereby affecting its porosity. Additionally, human activities such as agriculture, soil compaction by agricultural machinery, and land management practices can either increase or decrease soil porosity over time. For example, poor land management can lead to reduced porosity due to soil compaction, while appropriate conservation practices can improve soil structure and increase porosity. An initial and final evaluation is required (before and after rehabilitation) (USDA).

Link with ecological functions

Soil porosity is influenced by soil texture, structure (aggregation), rock fragment, organic matter content, and bulk density. Higher bulk density usually indicates lower porosity due to soil compaction, impacting water movement, aeration, and nutrient availability crucial for plant growth and soil health (USDA).

4.1.3. Compaction

Definition

Soil compaction is defined by the reduction of space between pores, resulting in a smaller pore volume and a greater soil density (DeJong-Hughes, 2018).

How to assess

The measurement of soil compaction is standardised by EN 13286-2 norm.

Application context

Compaction can change over time because of anthropogenic activities. Soils are sensitive to compaction, mainly due to their exposure to anthropogenic and climatic factors, as well as their texture and coarse and organic elements composition. An initial evaluation is required (before and after rehabilitation).

Link with ecological functions

Soil compaction directly influences parameters such as soil structure, aggregate stability, porosity, water retention capacity, permeability, water and nutrient availability for plants (USDA).

4.1.4. Soil depth

Definition

Soil depth refers to the distance from the soil surface to the underlying bedrock, parent material, or other hard or compacted layers. The “effective” soil depth then was considered the solum thickness (FAO, 2024).

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How to assess

Soil depth can be measured by digging a soil profile or with an auger.

Application context

Soil depth may vary very slowly in time (1cm every 100 to 1000 years!), therefore only an initial evaluation is required (before and after rehabilitation).

Link with ecological functions

Soil depth directly influences essential functions such as water retention, nutrient availability, and physical support for plants.

4.1.5. Aggregate stability

Definition

Aggregate stability refers to the soil's ability to maintain its structure against external forces like water erosion, wind, and mechanical disturbance. Stable aggregates are crucial for soil health, influencing water infiltration, root growth, and resistance to erosion (SINGH ET AL., 2022).

How to assess

The measurement of aggregate stability is standardised by ISO 10930:2012 and ASTM D7928-17 norms.

Application context

Aggregate stability should be evaluated initially and then periodically (e.g., every 2-3 years) to monitor changes due to soil management practices, climate conditions, or land use changes (ALGAYER ET AL., 2014). Monitoring must be carried out at the same climatic time period to reduce bias due to seasonal climatic influences.

Link with ecological functions

Aggregate stability is mainly influenced by soil texture, organic matter content, and soil biological activity. Soil aggregate stability influences soil structure, porosity, permeability, water retention capacity, water and nutrient availability (BISSONNAIS ET AL., 1995).

4.1.6. Soil bulk density

Definition

Soil density refers to the mass of soil per unit volume, including both solid particles and pore spaces (ALVES DE OLIVEIRA ET AL., 2015).

How to assess

The measurement of soil bulk density is standardised by ISO 11272:2017 and NFX 31-515 norms.

Application context

Soil density should be evaluated initially and periodically (e.g., annually or every 2-3 years) to monitor changes due to soil management practices, land use changes, or environmental conditions.

Link with ecological functions

Bulk density is closely related to soil texture, structure, porosity, compaction, root penetration, total water storage capacity and the infiltration rate.

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4.1.7. Soil water holding capacity

Definition

Soil water holding capacity refers to the maximum amount of water that soil can hold against gravity in its pore spaces after excess water has drained away. It is a key indicator of soil's ability to retain water for plant use (Skaalsveen et al., 2019).

How to assess

The measurement of water holding capacity is standardised by ISO 16586:2015 and ASTM D2325-17 norms.

Application context

An initial and final evaluation is required (before and after rehabilitation)

Link with ecological functions

Soil water holding capacity is influenced by soil depth, texture, structure, bulk density, compaction, root penetration, organic matter content, and soil water permeability.

4.1.8. Soil water availability

Definition

Available water refers to the portion of water in soil that can be absorbed by plant roots. It is the difference between field capacity (the amount of soil moisture remaining after excess water has drained) and the permanent wilting point (the minimal point of soil moisture the plant requires not to wilt).

How to assess

The measurement of water availability is standardised by ISO 11274:2014 norm and FAO Guidelines for Soil Description (4th edition).

Application context

An initial and final evaluation is required (before and after rehabilitation).

Link with ecological functions

Soil water availability directly affects plant growth, crop yield, and soil fertility. It is closely related to soil texture and structure as well as porosity, which influences water infiltration and water retention capacity.

4.1.9. Soil water permeability

Definition

Soil water permeability is the velocity or speed at which water enters into the soil. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour. An infiltration rate of 15 mm/hour means that a water layer of 15 mm on the soil surface, will take one hour to infiltrate.

How to assess

The measurement of soil permeability is not standardised but has standardized protocols, the most common of which is the Beerkan method (Lassabatere et al., 2019**)**.

Application context

As the soil water infiltration rate does not vary in the time, only an initial evaluation is required (before and after rehabilitation). Additional revaluation can be done every 4-5 years after the rehabilitation, depending on the site management plan.

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Link with ecological function

Soil water permeability depends on soil texture and soil structure.

4.1.10. Soil organic matter

Definition

Soil organic matter can be defined as organic materials found in soil that are, or have been, part of living organisms. It is a continuum of materials at various stages of transformation due to biotic and abiotic processes (CHENU ET AL., 2024).

How to assess

The analysis of soil organic matter is not standardised. However, several standardized protocols and methods exist, including the Rock-Eval® thermal analysis method (BEHAR ET AL., 2006).

Application context

Soil organic matter can be highly dynamic in the soil, therefore one revaluation per year is recommended.

Link with ecological functions

Soil organic matter directly impactes many soil abiotic and biotic properties such as soil structure, water permeability and soil fertility including nutrient availability related to plant growth and crop yield. Organic matter can bind to pollutants and make them inactive in the soil.

4.1.11. Soil organic carbon

Definition

Soil organic carbon is the main component of soil organic matter. SOC is one of the largest terrestrial carbon pools, playing a vital role in regulating a wide range of biological functions and ecosystem processes such as nutrient mobilization, cycling, availability, sequestration, and global carbon dynamics

How to assess

The analysis of soil organic carbon is not standardised. However, several standardized protocols and methods exist, including the Rock-Eval® thermal analysis method (BEHAR ET AL., 2006).

Application context

Soil organic carbon can be highly dynamic in the soil, therefore one revaluation per year is recommended.

Link with ecological functions

Soil organic carbon directly impacts many soil abiotic and biotic properties such as soil structure, water permeability and soil fertility including nutrient availability related to plant growth and crop yield.

4.1.12. Thermolabile carbon

Definition

Pool of organic carbon linked to hydrocarbon compounds in soil organic matter that crack between 200 and 400°C during the pyrolysis phase of the Rock-Eval analysis.

How to assess

The analysis of thermolabile carbon is not standardised. However, several standardized protocols and methods exist, including the Rock-Eval® thermal analysis method (SEBAG ET AL., 2016).

Application context

Thermolabile can be highly dynamic in the soil, therefore one revaluation per year is recommended.

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Link with ecological functions

Thermolabile carbon is related to the organic matter fraction easily mineralizable by microorganisms such as bacteria and fungi and thus directly influences microbe activities and soil life.

4.1.13. Thermoresistant carbon

Definition

Pool of organic carbon linked to hydrocarbon compounds in soil organic matter that crack between 400 and 650°C during the pyrolysis phase of the Rock-Eval analysis.

How to assess

The analysis of thermoresistant carbon is not standardised. However, several standardized protocols and methods exist, including the Rock-Eval® thermal analysis method (SEBAG ET AL., 2016).

Application context

Thermoresistant is less dynamic than the thermolabile carbon in the soil but one revaluation per year is still recommended.

Link with ecological functions

Thermoresistant carbon is related to the organic matter fraction more difficult to mineralize by microorganisms such as bacteria and fungi and thus directly influences microbe activities and soil life.

4.1.14. Soil inorganic carbon

Definition

SIC refers to carbon present in the soil in non-organic mineral forms. This type of carbon is mainly composed of carbonates, such as calcium carbonate and magnesium carbonate. Unlike organic carbon, inorganic carbon is not derived from the decomposition of organic matter but results from geochemical processes and the decomposition of rocks.

How to assess

The analysis of soil inorganic carbon is not standardised. However, several standardized protocols and methods exist, including the Rock-Eval® thermal analysis method (BEHAR ET AL., 2006).

Application context

Soil inorganic matter can be highly dynamic in the soil, therefore one revaluation per year is recommended.

Link with ecological functions

Soil inorganic carbon is related to the mineral forms of carbon (mainly carbonate form) that can influence soil abiotic properties such as pH (soil with high carbonates are often alkaline soils).

4.1.15. pH water

Definition

pH Water is a measure of the acidity or alkalinity of a soil sample when mixed with distilled or demineralised water. It is a commonly used method for assessing soil pH, as it provides an indication of soil response under conditions close to those naturally encountered by plants.

How to assess

The measurement of soil pH water is standardised by ISO 10523:2008, ASTM D1293 and ČSN EN ISO/IEC 17025:2018 norms (SUMNER, 1994).

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Application context

As the soil pH water does not vary in the time, only an initial evaluation is required (before and after rehabilitation). Additional revaluation can be done every 4-5 years after the rehabilitation.

Link with ecological functions

pH water of soil is one of the main factors driving plant and microbe biodiversity as it directly influences the availability of nutrients in the soil. An alkaline pH can precipitate some pollutants and make them inactive.

4.1.16. Total nitrogen

Definition

Soil total nitrogen refers to all forms of nitrogen present in the soil, whether organic or inorganic. Total soil nitrogen is an important measure of soil fertility and its ability to support plant growth.

How to assess

Dry combustion with Elemental analyzer named Dumas' method (ISO 13878:2013) or Kjeldahl's method (ISO 11261:1995)

Application context

Soil total nitrogen can be highly dynamic in the soil, therefore one revaluation per year is recommended.

Link with ecological functions

Soil total nitrogen is mainly related to the soil organic matter and can its availability depend on several soil properties such as pH and the different forms of the organic matter.

4.1.17. Mineral Nitrogen

Definition

Soil mineral nitrogen refers to the forms of nitrogen present in the soil in inorganic form, directly available for uptake by plants. Unlike organic nitrogen, which has to be broken down by micro-organisms to become available, mineral nitrogen can immediately be used by plants.

How to assess

Mineral Nitrogen is classically measured by colorimetric method following ISO 14256:2005 norm and USEPA Method 353.2 (Sattolo et al., 2016).

Application context

Mineral nitrogen can be highly dynamic in soil, therefore one revaluation per year is recommended.

Link with ecological functions

Mineral nitrogen is mainly related to soil organic matter and can it depend on the different forms of the organic matter in soil as well as biological activities.

4.1.18. Total phosphorus

Definition

Soil total phosphorus refers to all the forms of phosphorus present in the soil, whether organic or inorganic. Phosphorus is an essential element for plant growth, playing a crucial role in energy processes, photosynthesis and the formation of nucleic acids.

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How to assess

The total phosphorus is measured following the standardised Acid Digestion Method (ISO 11263; ASTM D2974)

Application context

Total phosphorus can be highly dynamic in the soil, therefore one revaluation per year is recommended.

Link with ecological functions

Total phosphorus is mainly related to the forms of the soil organic matter and depend on several soil properties such as pH and soil biological activities

4.1.19. Phosphorus availability

Definition

Assimilable or Available phosphorus in the soil, also known as available phosphorus or extractable phosphorus, is the fraction of total phosphorus present in the soil that can be absorbed and used by plants.

How to assess

The Olsen method is the most commonly used for measuring the available phosphorus (ISO 11263:1994)

Application context

Available phosphorus can be highly dynamic in the soil, therefore one revaluation per year is recommended.

Link with ecological functions

Available phosphorus is mainly related to the forms of the soil organic matter as well as biological activities such as bacteria solubilizing phosphorus from inorganic forms.

4.1.20. Cationic exchangeable capacity

Definition

The cation exchange capacity (CEC) of a soil is a measure of its ability to retain and exchange cations (positively charged ions) between soil particles and the soil solution. This property is crucial to soil fertility, as it influences the availability of nutrients to plants.

How to assess

The three methods for measuring cationic exchangeable capacity are: the ammonium acetate method (ASTM D7503), the barium chloride method (ISO 23470), and the cobalt hexammine method (EN 13041) (Chapman, 1965).

Application context

As the CEC may vary slowly in time, only an initial evaluation is required (before and after rehabilitation). Additional revaluation can be done every 4-5 years after the rehabilitation.

Link with ecological functions

The cationic exchangeable capacity is related to several soil properties such as pH, texture (clayey soil have higher CEC) and organic matter.

4.1.21. Carbon / Nitrogen ratio

Definition

The C/N ratio, or carbon/nitrogen ratio, is a measure of the proportion of carbon (C) to nitrogen (N) in organic matter present in the soil. This ratio is an important indicator of the decomposition of organic matter and the availability of nutrients for plants and soil micro-organisms.

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How to assess

The C/N ration is calculated by dividing the proportion of carbon and nitrogen in the soil organic matter (OSTROWSKA & POREBSKA, 2015).

Application context

C/N ratio can be highly dynamic in the soil, therefore one revaluation per year is recommended.

Link with ecological functions

C/N ratio mainly depends on the form and properties of the organic matter in the soil.

4.1.22. Granular composition

Definition

The granular composition of soils is determined by the relative percentage of different size fractions of soil particles. An important criterion is the percentage of the fraction with a grain size below 0.01 mm. It is a basic physical-mechanical test of soils from the point of view of their recultivation use. Medium-grained to fine-grained, even-grained rocks are most suitable for recultivation.

How to assess

The measurement of granular composition is standardised by the ČSN EN ISO/IEC 17025:2018 norm.

Application context

The granular composition can be evaluated at the initial time and during a short term and long term monitoring.

Link between each function

The granular composition of the soil significantly affects the possibility of the growth of woody plants and thereby affects biodiversity. Determining the grain size composition is important for describing the structure and texture of the soil. Granularity is also of fundamental importance for the water regime of the site. Acceptable values for the content of the granular fraction below 0.01 mm are in the range of 25 - 60%.

4.1.23. Concentrations of TMs (total and extractable)

Definition

- The **total concentration of trace metals** (TMs) in the soil is the amount of these TMs in a mass of soil.
- The **extractable concentration of TMs** (or phytoavailable fraction) is the ability of a TM to migrate from the solid phase of the soil to the soil solution and become bioavailable to the plant. Thus, if the extractable concentrations of TMs in the soil are high, the soil-plant transfers of TMs can also be high and result in a phenomenon of bioconcentration of TMs in the plant at concentrations higher than those present in the soil. The extractable concentration of a TM represents less than 1% of the total concentration of the TM.

As part of the analyses conducted by INERIS, the extractable and total concentrations of TMs in the soil are studied, such as cadmium (Cd) and lead (Pb), which are the TMs of greatest concern in terms of risks to the human population and surrounding ecosystems (phytotoxicity).

How to assess

- The total concentrations of TMs in the soil are obtained using the standard NF-EN-13656 "Characterization of waste - Microwave-assisted digestion with a mixture of hydrofluoric (HF), nitric (HNO3), and hydrochloric (HCl) acids for the subsequent determination of elements contained in waste".
- The extractable concentrations of TMs in the soil are obtained using the standard ISO 19730 (2008) "Soil quality - Extraction of trace elements from soil using a solution of ammonium nitrate (NH4NO3)".

The extractable and total concentrations of TMs are analyzed either by ICP-OES (Agilent 5100) or ICP-MS (Agilent 7500) depending on sample concentrations.

Application context

The concentrations of TMs (total and extractable) are to be determined for the initial characterization of the experimental plot as well as for a health risk assessment by specifically analyzing the extractable concentrations. The total and extractable concentrations should be measured after selecting the vegetation covers to observe their influence on these concentrations. The extractable and total concentrations of TMs will allow the calculation of the mobility percentage of the TMs studied.

Link between each function

The extractable concentration of a TM is related to its mobility in the soil, which depends on soil properties such as pH, redox potential, and cation exchange capacity (CEC) (Kabata-Pendias, 2010; Leschber et al., 1985) and soil constituents such as organic matter content and carbonate content.

4.1.24. Percentage of mobility

Definition

The percentage of TM mobility in the soil corresponds to the portion of the total fraction that is extractable (phytoavailable). It allows the classification of TMs from the most mobile to the least mobile. The more mobile a TM is in the soil, the higher the soil-plant transfers.

How to assess

TM mobility was calculated as follows:

% mobility = [TM] extractable soil / [TM] total soil * 100

Application context

The mobility percentage needs to be determined for the initial characterization of the experimental plot. It should be measured after selecting the vegetation covers to observe their influence on the mobility of the TMs.

Link between each function

The mobility of TMs in the soil depends on soil properties such as pH, redox potential, and cation exchange capacity (CEC) (Leschber and Worthington 1984; Kabata-Pendias, 2010), as well as soil constituents such as organic matter content and carbonate content.

4.1.25. As content

Definition

Arsenic is the only risky trace element for health and environment that occurs in significantly dangerous concentrations in the soils of the Most Basin. Its source is coal seam soils and, above all, soils affected by the wash from the nearby Ore Mountains (ores of non-ferrous metals).

How to assess

The measurement of As content is standardised by the ČSN EN ISO/IEC 17025:2018 norm.

Application context

Initial, short term (only at sites where elevated content was detected during the initial survey), long term (only at sites where elevated content was detected during the initial survey together with other risk trace elements according to Decree No. 153/2016 Coll.

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Link between each function

The increased content of arsenic is (at least in the conditions of the Most Basin) an important cause of soil contamination. They can also occur in topsoil on agriculturally reclaimed areas.

4.1.26. Fe sulfides content

Definition

The occurrence of iron sulfides (pyrite and marcasite) in reclaimed sites is possible only in sites with soils from coal seam layers.

How to assess

The measurement of Fe sulphides content is standardised by the **ČSN EN ISO/IEC 17025:2018** norm.

Application context

This parameter must be measured at the beginning of the rehabilitation.

Link between each function

The occurrence of iron sulfides (pyrite and marcasite) in soils leads to their gradual decomposition into sulfates, adversely affects pH and causes soil contamination. Their presence in the soil is undesirable.

4.1.27. Gypsum content

Definition

Crystalline gypsum occurs in some types of Tertiary clays. They form macroscopically visible white coatings and crystals.

How to assess

The measurement of gypsum content is standardised by the **ČSN EN ISO/IEC 17025:2018** norm.

Application context

Initial, short term (only at sites where elevated content was detected during the initial survey), long term (only at sites where elevated content was detected during the initial survey)

Link between each function

The occurrence of gypsum is an important source of soil contamination (salinization). It causes an extremely alkaline soil reaction, the death of a few trees and thus adversely affects biodiversity and possible forest reclamation. The presence of gypsum in the soil is undesirable.

4.1.28. Sulphur content

Definition

The occurrence of sulphur in reclaimed sites is possible only in sites with soils from coal seam layers. It occurs on similar surfaces as iron sulphides.

How to assess

The measurement of sulphur content is standardised by the **ČSN EN ISO/IEC 17025:2018** norm.

Application context

This parameter must be measured at the beginning of the rehabilitation.

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Link between each function

The occurrence of iron sulphides (pyrite and marcasite) in soils leads to their gradual decomposition into sulphates, adversely affects pH and causes soil contamination. Their presence in the soil is undesirable.

4.2. Biotic parameters

Table 2. Link between biotic parameters and ecological functions

Parameter	Habitat and biodiversity regulation	Nutrient capture for soil organisms and plants	Organic matter storage and cycling	Soil structure maintenance for plants	Water retention and infiltration	Pollutant attenuation and degradation
Microbiological diversity	✓	✓	✓			
Functional diversity based on functional genes		✓	✓			✓
Soil microbial biomass	✓	✓	✓			✓
Microbial CO_2 emission		✓	✓			
Enzyme activities linked to nitrogen cycle	✓	✓				
Enzyme activities linked to carbon cycle	✓	✓	✓			
Enzyme activities linked to phosphorus cycle	✓	✓				
Enzyme activities linked to sulfur cycle	✓	✓				
FDA activity	✓	✓	✓			
Leaf chlorophyll concentration	✓	✓	✓	✓	✓	✓
Vegetation Cover Index (VCI)	✓	✓	✓	✓	✓	✓
Contribution of plant species occurring in undisturbed ecosystem	✓	✓	✓	✓	✓	✓
Contribution of invasive species	✓	✓	✓	✓	✓	✓
Contaminant plant uptake, immobilization and degradation	✓	✓	✓	✓	✓	✓

4.2.1. Microbial diversity

Definition

Microbial diversity in soil refers to the variety and abundance of microorganisms, including bacteria, fungi, archaea, and viruses, present in the soil ecosystem. This diversity is crucial for maintaining soil health and ecological functions, as it influences nutrient cycling, organic matter decomposition, pollutant degradation, and overall soil fertility (Torsvik & Øvreås, 2002).

How to assess

Microbial diversity can be measured by quantitative polymerase chain reaction (qPCR) amplification, which allows for the measurement of the abundance of specific microbial gene sequences from a soil DNA extract, thereby providing an estimate of the abundance of specific microbial groups (ISO 17601:2016).

Application context

Monitoring microbial diversity is essential for soil rehabilitation and ecosystem management due to its sensitivity and robustness as an indicator. Microbial diversity responds to changes in environmental conditions and soil management practices, making it a reliable tool for assessing soil health (Jung et al., 2016). High microbial diversity is often linked to improved soil functions, such as enhanced nutrient cycling and organic matter decomposition, which are indicators of better soil quality (Nannipieri et al., 2003). This makes microbial diversity useful for both short-term and long-term monitoring: short-term monitoring can evaluate the immediate impacts of soil management practices, while long-term monitoring can assess the sustainability of these practices over time (Delgado-Baquerizo et al., 2016).

Link with ecological soil functions

Habitat and biodiversity regulation function: Microbial diversity contributes to the regulation of habitat and biodiversity by supporting various ecological niches and maintaining ecosystem stability. Diverse microbial communities promote a balanced ecosystem where various organisms can thrive (Zak et al., 2003).

Nutrient capture for soil organisms and plants function: Microbial diversity significantly impacts nutrient cycling and availability in soils. Diverse microbial communities with varied functional genes improve nutrient capture and recycling, supporting plant growth and soil organism health through processes such as nitrogen fixation and phosphorus solubilization (Philippot et al., 2013).

Organic matter storage and cycling function: Microbial functional diversity plays a crucial role in organic matter decomposition and carbon cycling. Enzymes encoded by diverse functional genes facilitate the breakdown of complex organic compounds, enhancing soil carbon storage and mitigating greenhouse gas emissions. This contributes to maintaining soil structure and fertility (Maron et al., 2018).

4.2.2. Functional diversity based on functional genes

Definition

Functional diversity based on functional genes refers to the variety and abundance of functional genes within soil microbial communities. These genes encode enzymes and proteins that drive various ecological processes, such as nutrient cycling, organic matter decomposition, and pollutant degradation. Functional diversity is a crucial indicator of soil health and ecosystem functionality, as it reflects the potential of soil microorganisms to perform essential ecological functions (Torsvik & Øvreås, 2002).

How to assess

Functional diversity can be measured by quantitative polymerase chain reaction (qPCR) amplification, which allows for the measurement of the abundance of specific microbial gene sequences from a soil DNA extract, thereby providing an estimate of the abundance of specific microbial groups (ISO 17601:2016).

Application context

Monitoring functional diversity is essential for soil rehabilitation and ecosystem management, offering a sensitive and robust indicator of soil quality and health. Functional diversity responds to changes in environmental conditions and soil management practices, making it a reliable tool for tracking soil health (Reeve et al., 2010). High functional diversity is often linked to improved soil functions, such as enhanced nutrient cycling and organic matter decomposition, which indicate better soil quality (Jung et al., 2016). This indicator is useful for both short-term and long-term monitoring: short-term assessments can detect immediate impacts of soil management practices, while long-term monitoring evaluates the sustainability of these practices over time (Torsvik & Øvreås, 2002).

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Link with ecological soil functions

Nutrient capture for soil organisms and plants function: functional diversity significantly impacts nutrient cycling and availability in soils. Diverse microbial communities with varied functional genes improve nutrient capture and recycling, supporting plant growth and soil organism health through processes such as nitrogen fixation and phosphorus solubilization (FIERER ET AL., 2012).

Organic matter storage and cycling function: Microbial functional diversity plays a crucial role in organic matter decomposition and carbon cycling. Enzymes encoded by diverse functional genes facilitate the breakdown of complex organic compounds, enhancing soil carbon storage and mitigating greenhouse gas emissions. This contributes to maintaining soil structure and fertility (XUN ET AL., 2021).

Pollutant attenuation and degradation function: Functional diversity plays a critical role in the degradation of pollutants. Diverse microbial communities with varied functional genes enhance the breakdown and detoxification of contaminants, leading to reduced pollutant levels in soils. Genes involved in the degradation of hydrocarbons and other pollutants are often enriched in diverse soil microbial communities (GILL ET AL., 2017).

4.2.3. Soil microbial biomass

Definition

Soil microbial biomass refers to the living component of soil organic matter, excluding plant roots and soil animals larger than about 5.10^{-3} mm^3. It includes a diverse community of microorganisms, such as bacteria, fungi, archaea, protozoa, and algae, that play crucial roles in soil processes. These microorganisms are responsible for the decomposition of organic matter, nutrient cycling, and the formation of soil structure. The microbial biomass is a key indicator of soil health and fertility, as it influences nutrient availability, soil organic matter dynamics, and the overall productivity of terrestrial ecosystems.

How to assess

Soil microbial biomass can be indirectly estimated using various methods. Firstly, there are two specific methods that allow for its quantification. The first method involves extracting organic carbon and nitrogen from the soil after fumigating the soil with chloroform to kill and degrade the microorganisms (ISO 14240-2). The second method is a phospholipid fatty acid analysis (PLFA) which identifies and quantifies the microbial community composition based on the extraction of phospholipid fatty acids from soil samples (ISO/TS 29843-2:2021). An estimation of active microbial biomass can also be inferred from induced soil microbial respiration (ISO 17155:2012) and certain enzymatic activities related to the metabolism of microorganisms.

Application context

Soil microbial biomass monitoring helps to assess the effectiveness of soil restoration efforts. An increase in soil microbial biomass indicates improved soil health. This indicator is sensitive to changes in soil environmental conditions and management and well related to other soil quality indicators. It provides early indications of soil quality changes before they become apparent through other biological indicators, making microbial biomass a suitable indicator for short-term monitoring.

Link with ecological soil functions

Habitat and biodiversity regulation function: Soil microbial biomass contributes to habitat creation and maintenance for a diverse range of soil organisms. A rich microbial community supports higher biodiversity, which is essential for ecosystem resilience and function.

Nutrient capture for soil organisms and plants function: Microorganisms decompose organic matter, releasing nutrients such as nitrogen, phosphorus, and sulfur in forms that plants and other soil organisms can absorb. This process ensures the availability of essential nutrients for plant growth and soil fertility.

Organic matter storage and cycling function: Microorganisms are involved in the decomposition of organic matter, transforming it into stable forms that contribute to soil organic matter storage. This process enhances carbon sequestration, which are vital for long-term soil health and climate regulation.

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Pollutant attenuation and degradation : The increase in soil microbial biomass is often associated with a better capacity for contaminant degradation and more effective pollution attenuation. This relationship is due to the multiplication of microorganisms capable of metabolizing and neutralizing toxic substances (Venkateswarlu et al., 2016; Margesin et al., 2007).

4.2.4. Soil microbial CO2 emission

Definition

Soil microbial respiration is a biological process in which soil microorganisms, including bacteria, fungi, and other microbes, break down organic matter, converting it into carbon dioxide (CO_2) and releasing it into the atmosphere. This process reflects the metabolic activity of the soil microbial community and is a critical component of the global carbon cycle. This activity, essential for nutrient cycling, is a key indicator of microbial activity and soil health (Weldmichael et al., 2020). High respiration rates generally indicate a rich, active microbial community and a high level of organic matter decomposition, which are signs of healthy or fertile soil (Hanson et al., 2000).

How to assess

Various methods are used to measure soil microbial respiration, including basal respiration and substrate-induced respiration. Basal respiration measures the natural CO_2 production by soil microbes, while substrate-induced respiration involves adding a specific substrate to stimulate microbial activity and measure the resulting CO_2 production. Soil microbial respiration can be measured in-situ or ex-situ with several standardised protocols (e.g. ISO 17155:2012, ISO 16072:2002)

Application context

Soil microbial CO_2 emissions provide insights into the biological activity and health of soils undergoing rehabilitation. Increased microbial activity often indicates successful restoration efforts. Just like the soil microbial biomass indicator, microbial respiration is sensitive to environmental changes in the soil as well as management practices. This makes it a good short-term indicator as well. The use of this indicator over the long term also allows for understanding soil carbon dynamics.

Link with ecological soil functions

Nutrient capture for soil organisms and plants function: Soil microbial respiration is indicative of the overall metabolic activity within the soil. During the decomposition of organic matter by microorganisms, they release nutrients such as nitrogen (N), phosphorus (P), and sulfur (S) back into the soil in forms that plants can absorb. This process is vital for sustaining plant growth and maintaining soil fertility (Sha et al., 2013).

Organic matter storage and cycling function: Soil microbial respiration is a major pathway through which carbon stored in soil organic matter is returned to the atmosphere as CO_2. It plays a crucial role in the global carbon cycle and influences soil carbon dynamics and storage capacity (Karhu et al., 2014).

4.2.5. Enzyme activities linked to nitrogen cycle

Definition

Enzyme activities linked to the nitrogen (N) cycle refer to the biological processes facilitated by soil enzymes, which are crucial for the transformation and cycling of nitrogen within the soil. These enzymes, produced mainly by soil microorganisms but also by plants and animals, include urease, nitrate reductase, and arylamidase, among others. These enzymes play a significant role in the breakdown of organic matter and the conversion of nitrogen into forms accessible to plants and other soil organisms. Urease breaks down urea into carbon dioxide and ammonium. Its activity is generally stimulated by the addition of organic matter, which promotes microbial growth, and the amount produced depends on the type of available organic matter. Urease can be quickly degraded in the soil by proteolytic enzymes but is more stable when associated with soil colloids. This enzyme, primarily produced by bacteria and fungi, catalyses the hydrolysis of urea, amides, and carboxylic acids.

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How to assess

The measurement of soil enzyme activity is gerneally done using colorimetric or fluorimetric substrates. This method relies on the use of soil sample solutions and colorimetric substrates, which are incubated for specific durations. The colour intensities are measured by absorbance using a UV/visible spectrophotometer (ISO 20130:2018) or a fluorimeter.

Application context

High enzyme activity generally correlates with better soil health, higher organic matter content, and improved nutrient availability, all of which are essential for sustainable land management (Fatemi et al., 2016).

Link with ecological soil functions

Habitat and biodiversity regulation function: The increase in microbial enzyme activity is closely linked to the improvement of soil habitat function and biodiversity by promoting nutrient availability, organic matter decomposition, and supporting a diverse and resilient fauna and flora. (Lavelle & Spain, 2001)

Nutrient capture for soil organisms and plants function: These enzymes play a crucial role in breaking down organic matter and converting nitrogen into forms that plants and soil organisms can readily absorb. This process is vital for maintaining soil fertility and supporting plant growth (Xiao et al., 2020).

4.2.6. Enzyme activities linked to carbon cycle

Definition

Enzyme activities linked to the carbon (C) cycle refer to the biochemical processes facilitated by soil enzymes that decompose organic matter and convert carbon into forms that are available for plant and microbial use. Key enzymes involved in the carbon cycle include β-glucosidase, cellulase, and lignin peroxidase, among others. These enzymes are produced by soil microorganisms and play a crucial role in the degradation of complex organic compounds. The β-glucosidase (β-GLU) plays a role in the final step of cellulose degradation to produce glucose and is highly sensitive to pH changes and soil management practices. N-acetyl-glucosaminidase (NAG) degrades chitin chains by hydrolyzing glycosidic bonds. Chitinases can be derived from plants (induced by microbial infection), fungi (promoting symbiotic interactions with plants), and bacteria (mainly produced by actinomycetes).

How to assess

The measurement of soil enzyme activity is traditionally done using colorimetric substrates. This method relies on the use of soil sample solutions and colorimetric substrates, which are incubated for specific durations. The color intensities are measured by absorbance using a UV/visible spectrophotometer (ISO 20130:2018)

Application context

Enzymes involved in the carbon cycle are primarily responsible for transforming soil organic matter, either by mineralizing it or converting it into stable molecules. Similar to enzymes in the nitrogen cycle, carbon cycle enzymes respond rapidly to environmental conditions. Consequently, they enable short-term monitoring while also providing insights into the long-term dynamics of the carbon cycle.

Link with ecological soil functions

Habitat and biodiversity regulation function: The increase in microbial enzyme activity is closely linked to the improvement of soil habitat function and biodiversity by promoting nutrient availability, organic matter decomposition, and supporting a diverse and resilient fauna and flora. (Lavelle & Spain, 2001)

Nutrient capture for soil organisms and plants function: By modifying organic compounds, enzymes directly or indirectly release nutrients such as nitrogen or phosphorus in forms that are easily transformed and assimilated by organisms such as plants.

Organic matter storage and cycling function: Enzymes involved in the carbon cycle contribute to the decomposition of organic matter, transforming it into stable forms that contribute to soil organic matter storage. This process enhances soil structure, promotes organic matter storage, and improves water retention capabilities.

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Effective organic matter cycling is crucial for maintaining long-term soil health and climate regulation (FENG ET AL., 2019).

4.2.7. Enzyme activities linked to phosphorus cycle

Definition

In the soil, organic phosphorus can represent up to 90% of the total phosphorus pool (RICHARDSON & SIMPSON, 2011). This organic phosphorus must be converted into mineral phosphorus to be absorbed by organisms. This conversion is mainly carried out through the intervention of phosphatases of various biological origins (bacteria, fungi, plants, etc.). Acid phosphatase (PAC) originates from root exudates, while alkaline phosphatase (PAK) is produced by bacteria and fungi, especially mycorrhizal fungi. These phosphatases differ based on the optimal pH for their activity

How to assess

The measurement of soil enzyme activity is traditionally done using colorimetric substrates. This method relies on the use of soil sample solutions and colorimetric substrates, which are incubated for specific durations. The color intensities are measured by absorbance using a UV/visible spectrophotometer (ISO 20130:2018)

Application context

Phosphorus is one of the limiting nutrients in the soil for the growth of organisms. The recycling of organic phosphorus and its mineralization are necessary to make it assimilable. The activity of phosphatases, which make this mineralization possible, depends on soil quality. Similar to enzymes in the nitrogen cycle and carbon cycle, phosphorus cycle enzymes enzymes respond rapidly to environmental conditions. Consequently, they enable short-term monitoring while also providing insights into the long-term dynamics of the phosphorus cycle.

Link with ecological soil functions

Habitat and biodiversity regulation function: The increase in microbial enzyme activity is closely linked to the improvement of soil habitat function and biodiversity by promoting nutrient availability, organic matter decomposition, and supporting a diverse and resilient fauna and flora. (LAVELLE & SPAIN, 2001)

Nutrient capture for soil organisms and plants function: These enzymes play a crucial role in the decomposition of organic phosphorus compounds, contributing to phosphorus recycling. By releasing phosphorus in mineral forms that plants and soil organisms can easily absorb, the enzymes promote plant growth.

4.2.8. Enzyme activities linked to sulfur cycle

Definition

Soil enzyme activities linked to the sulfur cycle primarily involve enzymes such as arylsulfatase and sulfite oxidase. Arylsulfatase catalyzes the hydrolysis of sulfate esters, releasing inorganic sulfate essential for plant and microbial nutrition. Sulfite oxidase converts sulfite to sulfate, a crucial step in sulfur mineralization. These enzymes are critical indicators of sulfur cycling, reflecting the soil's biochemical capacity to process sulfur compounds and maintain ecological balance.

How to assess

The measurement of soil enzyme activity is traditionally done using colorimetric substrates. This method relies on the use of soil sample solutions and colorimetric substrates, which are incubated for specific durations. The color intensities are measured by absorbance using a UV/visible spectrophotometer (ISO 20130:2018)

Application context

Sulfur is an essential trace element for plants; it is involved in the composition of certain amino acids and chloroplasts, and also plays a role in the formation of secondary metabolites. Just like nitrogen or phosphorus, only mineral sulfur can be absorbed. As with other enzyme groups, an increase in enzymatic activities related to the sulfur cycle tends to indicate an improvement in soil quality, making them valuable for assessing the impact of restoration practices on soil quality.

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Link with ecological soil functions

Habitat and biodiversity regulation function: The increase in microbial enzyme activity is closely linked to the improvement of soil habitat function and biodiversity by promoting nutrient availability, organic matter decomposition, and supporting a diverse and resilient fauna and flora. (LAVELLE & SPAIN, 2001)

Nutrient capture for soil organisms and plants function: Sulfur cycle enzymes play a pivotal role in nutrient capture for soil organisms and plants by mobilizing nutrients, decomposing soil organic matter, and enhancing ecosystem productivity. Enzymes like arylsulfatase help release sulfate from organic matter, making it available for plant uptake and microbial use (TURNER, 2010). This process is crucial for the growth and productivity of soil biota and plants. Additionally, these enzymes contribute to the breakdown of complex organic compounds, facilitating nutrient cycling and improving soil fertility (BALDRIAN, 2018; CHEN ET AL., 2016). By maintaining the sulfur cycle, these enzymes support the overall productivity and stability of soil ecosystems, enhancing biodiversity and ecosystem services (WAN-QIN, 2002).

4.2.9. FDA activity

Definition

Fluorescein diacetate (FDA) hydrolysis is a biochemical assay used to measure total microbial activity in soils. The FDA is a colorless, non-fluorescent compound that, when hydrolyzed by microbial enzymes such as esterases, lipases, and proteases, produces a fluorescent product, fluorescein, which can be quantitatively measured. This process is indicative of the overall metabolic activity of soil microorganisms, making it a valuable indicator of soil health and microbial function (SCHNÜRER & ROSSWALL, 1982).

How to assess

The most common method for measuring FDA activity is through spectrophotometry. The fluorescein produced by the hydrolysis reaction is measured at 490 nm using a spectrophotometer (GREEN ET AL., 2006).

Application context

FDA hydrolysis is sensitive to changes in microbial activity and can be influenced by soil type, organic matter content, and environmental stressors such as pollutants (TAO ET AL., 2021). Its robustness can be ensured by optimizing assay conditions for different soil types. The hydrolytic activity of FDA correlates well with other soil health indicators, such as microbial biomass and respiration, making it a reliable proxy for overall soil quality (SÁNCHEZ-MONEDERO ET AL., 2008). Additionally, FDA hydrolysis is suitable for both short-term and long-term monitoring; in the short term, it can assess the immediate impact of soil amendments or pollutants, while in the long term, it can track changes in soil health over time due to management practices.

Link with ecological soil functions

Habitat and biodiversity regulation function: The increase in microbial enzyme activity is closely linked to the improvement of soil habitat function and biodiversity by promoting nutrient availability, organic matter decomposition, and supporting a diverse and resilient fauna and flora. (LAVELLE & SPAIN, 2001)

Nutrient capture for soil organisms and plants function: FDA hydrolysis is closely linked to nutrient cycling in soil, serving as an indicator of microbial activity and plant-microbe interactions. High FDA hydrolysis rates signify active microbial communities that decompose organic matter, thereby releasing essential nutrients for plant growth (CHAKRABARTI & BHATTACHARYYA, 2006). Additionally, these active soil microbes enhance nutrient availability through processes such as nitrogen fixation and phosphate solubilization, further supporting healthy plant growth (PERUCCI, 1992).

Organic matter storage and cycling function: FDA hydrolysis significantly influences organic matter dynamics by promoting decomposition and enhancing carbon sequestration. Microbial enzymes involved in FDA hydrolysis break down complex organic matter into simpler forms, facilitating their utilization by soil organisms and promoting organic matter turnover (SÁNCHEZ-MONEDERO ET AL., 2008). This efficient microbial decomposition not only boosts soil fertility but also contributes to carbon sequestration, thereby playing a vital role in mitigating climate change (TOKUDA & HAYATSU, 2002).

4.2.10. Leaf chlorophyll concentration

Definition

Leaf chlorophyll concentration can indirectly reflect the status of vegetation health. Chlorophyll (mainly chlorophyll a and chlorophyll b (Cab)) is the main pigment facilitating photosynthesis and plays a critical role in the energy metabolism of green plants by converting solar radiation into stored chemical energy. Such disruptions in chlorophyll metabolism have profound implications for plant growth and development. Chl characteristically absorbs wavelengths in the red and blue-violet spectrum, reflecting green light, thereby imparting a green hue to plant foliage. Plant development is subject to the influence of both intrinsic and extrinsic factors, with external elements. Abiotic stress factors, including for example salt, temperature, flooding, light, and heavy metals, critically influence the expression of genes and the functionality of enzymes in Chl biosynthesis. These stressors play an integral role in regulating plant growth and development, with significant implications for crop yields and economic productivity. Environmental fluctuations, particularly abiotic stressors such as drought, extreme temperature variations, and excessive light exposure, can also significantly perturb the metabolic pathways governing chlorophyll biosynthesis and catabolism. The results of studies reported in the literature indicate that chlorophyll content can be treated as a universal indicator of plant health, including indirectly as an indicator of soil quality.

In accordance with the objectives of Task 5.1, focusing on plant indicators and vegetation characteristics that indicate the state of ecosystem development within the framework of restoration processes, it is assumed to use the chlorophyll content index in leaves. On the one hand, this proposed indicator may be a multipurpose tool for assessing the condition of plants in response to habitat conditions and quality of soil, but on the other hand, in order to comprehensively analyze the results obtained, it may be necessary to analyze in the context of other indicators studied to determine the more complex relationship. According to the work planned in the project, during field work, the relative chlorophyll content is a suitable indicator, indirectly indicating the quality of the soil. In addition, the non-invasiveness of the measurement method and the quick reading of the results using a portable device are undoubted advantages.

How to assess

The direct method for determining chlorophyll content in leaf tissues requires extraction of chlorophyll in a specific solvent, followed by spectrophotometric analysis of the solution. The result of this method is the amount of chlorophyll in the leaf, expressed as chlorophyll concentration in µg Chl per 1 g of tissue or chlorophyll content in µg Chl per 1 cm2 of tissue. The ratio of chlorophyll a to chlorophyll b can provide information on the impact of stress. **Optical methods** allow rapid and non-invasive determination of chlorophyll content. They are based on the **absorbance and/or reflectance** phenomena of a living leaf and the results obtained do not represent the chlorophyll content in relation to the leaf surface or its concentration in the tissue, but indicate the relative chlorophyll content. **Absorbance-based chlorophyll meters (chlorophyllometer)** measure the absorbance of a leaf with respect to wavelengths of light of two wavelengths: 620-660 nm (red light, absorbed by chlorophyll) and 930-960 nm as a reference radiation, used to match the measurement to the anatomical features of the leaf. The first device of this type available on the market was the SPAD-502 meter. Chlorophyll content can also be determined **by measuring reflected light**. Leaf cells reflect a significant portion of solar radiation in the near-infrared range (700-1100 nm), while their re-emission of visible light (400-700 nm) is relatively low due to absorption by photosynthetic pigments. The difference in visible and near-infrared light reflectance is used to calculate the so-called normalized difference vegetation index (NDVI). The accurately and non-destructively monitor chlorophyll on multiple scales has been developed. The chlorophyll content in leaf could be measure using spectral satelite data, UAV with spectrometer and handheld spectrometer and chlorophyllometer.

How to assess

The leaf chlorophyll concentration should be measured in long term, periodically at different stages of plant growth.

Link with ecological soil functions

The table n.2 presents the relationship between leaf chlorophyll concentration as soil biological and ecological parameters and ecological functions.

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4.2.11. Vegetation Cover Index (VCI)

Definition

The proportion of ground covered by vegetation is defined as the Vegetation Cover Index (VCI). It is a valuable tool for assessing soil health and the potential of ecosystems to perform ecosystem services. The Vegetation Cover Index (VCI) is also a crucial indicator for evaluating the effectiveness of reclamation efforts, particularly in disturbed or degraded landscapes such as mined lands, landfills, and areas affected by industrial activities. Vegetation Cover Index (VCI) measures the It is typically derived from remote sensing data (e.g., NDVI from satellite imagery see deliverable 3.1) or direct ground observations. The Vegetation Cover Index is a robust and effective indicator for assessing the success of reclamation efforts. The initial states of rehabilitated ecosystem could be evaluated using satellite data and aerial photos. By analyzing historical images, it is possible to determine how long it takes for spontaneous plant succession to occur in a given area. The time required for the development of vegetation in such an area indicates the conditions for its growth and depends primarily on the fertility of the soil. The results of the analysis may be the basis for determining the challenges of reclamation processes.

How to assess

Protocol: The detailed study of the structure of the plant community including the vegetation cover, contribution of plant species occurring in undisturbed ecosystems and invasive species is carried out on phytosociological inventories taken directly in the field. They involve systematically recording all the plant species within a defined area to understand the composition, structure, and dynamics of vegetation. Here's a step-by-step description of how phytosociological inventories are carried out:

I. Establishing the Plot

Consists in choosing representative area within the ecosystem or habitat type being studied. This area should be homogeneous in terms of vegetation and environmental conditions. Common plot sizes range from 1 m² for herbaceous vegetation to 1000 m² for forest communities. Rectangular or square plots are typically used. The stakes, flags, or other markers could be used to delineate the boundaries of the plot. The GPS coordinates of the plot should be also set for future observations

II. Vegetation Sampling

Identify and record all plant species within the plot. Use field guides, keys, or experts to ensure accurate identification. Note any difficulties or uncertainties in identification. Estimate the cover-abundance of each species using a scale such as the Braun-Blanquet scale, which typically includes:

- +: Few individuals, less than 1% cover
- 1: Abundant individuals, 1-5% cover
- 2: 5-25% cover
- 3: 25-50% cover
- 4: 50-75% cover
- 5: 75-100% cover

III. Recording Plant Heights

Measure and record the heights of the dominant plant species to understand the vertical structure of the vegetation.

Application context

initial/short term/long term

Link with ecological soil functions

See Table 2.

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4.2.12. Contribution of plants plant species occurring in undisturbed ecosystem

Definition

Plant species in undisturbed ecosystems often represent the baseline soil health and functionality of an ecosystem. Undisturbed ecosystems typically have high biodiversity, which is closely linked to ecosystem resilience and the ability to deliver multiple ecosystem services (e.g nutrient cycling, soil formation, and water regulation). Plant species occurring in undisturbed plant communities often deliver provisioning services such as food, medicine, and raw materials. They could provide information for assessing changes or degradation of ecosystem.

How to assess

see description as for VCI parameter

Application context

The characteristic plant species composition can serve as short and long-term indicators of ecosystem health, reflecting cumulative impacts over time.

Link with ecological soil functions

The interactions between plant communities' structures and ecosystems health can be complex, making it challenging to isolate specific indicators for particular ecosystem services (Table n.2). Overall, plant species in undisturbed ecosystems are valuable indicators of soil health and an ecosystem's potential to deliver ecosystem services. They offer insights into the baseline health, biodiversity, stability, and resilience of ecosystems. However, the complexity and context-specific nature of these ecosystems must be considered.

4.2.13. Contribution of invasive species

Definition

Invasive species pose significant threats to plant communities, leading to ecological, economic, and social impacts. Here are the key threats posed by invasive species in plant communities:

- Competition with native species: invasive species often outcompete native plants for vital resources such as light, water, nutrients, and space. Their aggressive growth can overshadow and suppress native species, altering plant community composition and reducing the diversity and abundance of native flora.
- Alteration of Ecosystem Processes: invasive species can alter soil nutrient cycles by changing the rates of nutrient uptake and release. For example, some invasive species can fix nitrogen at higher rates than native species, leading to nutrient imbalances (nutrient cycling). Some invasive plants can change water availability in ecosystems by increasing evapotranspiration (water cycle).
- Habitat Modification: they can modify the microhabitat conditions, such as light levels, temperature, and moisture, making it less favorable for native species.
- Loss of biodiversity
- Species Extinction: Aggressive invasive species can drive native species to local extinction by outcompeting them for resources or through direct suppression.
- Reduced Genetic Diversity: The dominance of invasive species can lead to a reduction in the genetic diversity of native plant populations, weakening the resilience of the ecosystem to environmental changes.
- Economic Impact Invasive plant species can invade agricultural lands, reducing crop yields, increasing management costs, and leading to economic losses. Some invasive species can also cause direct damage to the infrastructure. Significant resources are often required to manage invasive species, including monitoring, removal, and restoration efforts.
- Social and Cultural Impact: many native plants hold cultural significance for indigenous and local communities. Invasive species can threaten these culturally important plants. It can also impact recreational activities by altering landscapes and ecosystems, reducing the aesthetic and recreational value of natural areas.

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- Human health risk: invasive species can be toxic for people in case of contact (e.g. Caucasian hogweed contains a phototoxic sap that when exposed to light can cause severe burns on human skin) or can cause allergies.

Invasive species pose multifaceted threats to plant communities, leading to the loss of biodiversity, alteration of ecosystem services, disruption of mutualistic relationships, and significant economic and social impacts. Effective management and prevention strategies are essential to mitigate these threats and protect native ecosystems. Reclamation efforts must therefore be geared toward reducing the possibility of invasive species encroachment. It is also necessary to monitor newly developed ecosystems for this threat11.

How to assess

see description as for CVI parameter

Application context

The contribution of invasive species can indicate initial state and short and long-term changes in ecosystem health.

Link with ecological soil functions

see Table 2

4.2.14. Concentrations of TMs in plants

Definition

The concentration of TMs in plants is the amount of these TMs contained in the studied organ of the plant (stems, leaves, seeds, etc.). Furthermore, the concentrations of TMs in plants vary among individuals, cultivars, and species, with the latter exhibiting behaviors ranging from the exclusion to the accumulation of certain metals.

How to access

Washing the plants might be important if soil dust containing TMs settles on the aerial parts of the plants (Hibben et *al.*, 1984). If washing is performed, the plant materials are carefully washed with tap water and deionized water before being dried at 40°C until a constant weight is reached. The plant samples are mineralized with nitric acid (HNO3) following an internal standard at INERIS and then analyzed by ICP-OES (Agilent 5100) or ICP-MS (Agilent 7500).

Application context

The concentrations of TMs in plants are calculated for the most abundant plant species on the experimental site before the rehabilitation project to characterize soil-plant transfers (using the extractable and total concentrations of TMs in the soils) and to calculate the bioconcentration factor in the studied organ of the plant.

Link between each function

The concentrations of TMs in plants help determine if they are phytotoxic, and if so, they would reduce the number of plant species present on the experimental site.

4.2.15. Bioconcentration factor

Definition

The bioconcentration factor (BCF) allows observation of the behavior of TMs in the studied organ of the plant (stems, leaves, seeds, etc.). There are two types of BCF:

- The **extractable bioconcentration factor** (BCF ext) considers the extractable concentration of TMs in the soil.
- The **total bioconcentration factor** (BCF tot) considers the total fraction of TMs in the soil.

If the BCF tot is greater than 1, the plant is considered an accumulator of the studied TM. Otherwise, it is termed "excluder".

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How to assess

Bioconcentration factors (BCF) were calculated as follows:

- **BCF ext = [TM] plant / [TM] extractable soil**
- **BCF tot = [TM] plant / [TM] total soil**

Application context

The bioconcentration factor is calculated for the most abundant plant species on the experimental site before the rehabilitation project to characterize soil-plant transfers and the accumulator or non-accumulator behavior of these plant species with respect to TMs.

Link between each function

The bioconcentration factor is important for highlighting the accumulation of TMs by plants, which are the first links in the food chain. Indeed, if plants accumulate significant amounts of TMs, this will lead to a phenomenon of bioaccumulation throughout a trophic network, potentially resulting in extremely high concentrations in organisms at the top of the food chain (Liang et al., 2019). As a result, this poses a risk to the fauna present at the experimental site.

5. Large scale function assessment

Mining activities significantly impact the environment, affecting vegetation loss and biodiversity. Satellite imagery can be applied to examine spatial and temporal trends of superindicators such as NDVI and NDMI to assess rehabilitated mining quarries and adjacent natural areas. By employing NDVI and NDMI, which are sensitive to changes in vegetation and soil moisture, the research aims to assess the effectiveness of rehabilitation in restoring vegetation and water balance within mining-affected landscapes and to connect them with biological and ecological indicators. NDVI is directly connected with the overall soil productivity and biomass and NDMI with the soil water content (Erener, A. 2011; .Thakur, et al. 2022).

NDVI can be useful for monitoring vegetation health in rehabilitated mining quarries. Mining activities often destroy vegetation, and rehabilitation efforts aim to restore the vegetation cover. NDVI can be used to track the progress of vegetation restoration and identify areas that may require additional attention (Bouaziz & Benndorf, 2024).

The Normalized Difference Moisture Index (NDMI) is a remote-sensing vegetation index used to assess vegetation water content and soil moisture levels. It is valuable for monitoring changes in water content in vegetation and bare soil (Bouaziz, & Benndorf, 2024).

This project task aims to assess the effectiveness of NDVI and NDMI for monitoring vegetation health and soil water content in rehabilitated mining areas by employing Self-Organizing Maps (SOM). The proposed research has the potential to advance the field of environmental monitoring and management by enhancing the combined effect between remote sensing technologies and advanced data analysis techniques. By combining NDVI and NDMI with SOM, the research can provide a more comprehensive and accurate assessment of soil health in rehabilitated mining quarries and provide information on specific indicators (Table 3) that will assure regular monitoring of the case study areas. SOM can help in clustering and visualizing complex data patterns, enabling better monitoring and analysis. Sentinel satellite source images were used to determine NDVI and NDMI for the study area.

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Table 3. Link between soil biological and ecological parameters and ecological functions

Parameter	Habitat and biodiversity regulation	Nutrient capture for soil organisms and plants	Organic matter storage and cycling	Soil structure maintenance for plants	Water retention and infiltration	Pollutant attenuation and degradation
NDVI//Soil organic carbon	✓	✓	✓	✓	✓	✓
NDVI/Biomass productivity	✓	✓		✓		
Land surface temperature	✓	✓	✓		✓	
NDMI/Water holding capacity					✓	✓

5.1.1. Soil organic carbon

Definition

Soil organic carbon (SOC) refers to the carbon component of soil organic matter, which is derived from decomposed plant and animal materials. It plays a crucial role in soil health and fertility.

How to assess

There are several protocols and norms related to the measurement and management of soil organic carbon, but one commonly used standard is ISO 10694:1995, which specifies a method for the determination of organic carbon in soils.

Application context

In terms of revaluation, the initial assessment of soil organic carbon content is typically done as part of a baseline study or soil assessment. Subsequent revaluations can be done in the short term or in the long term to monitor changes in soil organic carbon levels due to land management practices, climate change, or other factors. Regular monitoring of soil organic carbon is important for sustainable land use and agricultural practices.

Link between each function

SOC has an important effect on crop growth status, and remote sensing data can record the apparent spectral characteristics of crops. The normalized difference vegetation index (NDVI) is an important index reflecting crop growth and biomass.

Soil organic carbon plays a critical role in supporting various ecosystem functions and services. It contributes to habitat and biodiversity regulation by providing nutrients for soil organisms, and sustaining a healthy soil ecosystem. Soil organic carbon also aids in nutrient capture for soil organisms and plants, acting as a reservoir of essential nutrients that are slowly released during decomposition. Furthermore, it is essential for organic matter storage and cycling, promoting nutrient availability for plant growth and microbial activity. Soil organic carbon contributes to soil structure maintenance by enhancing aggregation, improving soil porosity, water retention, and infiltration, which benefit plant root growth and overall plant health. Additionally, soil organic carbon plays a role in pollutant attenuation and degradation by binding to and degrading pollutants, thereby reducing their impact on the environment. Overall, managing soil organic carbon levels is crucial for maintaining healthy soils, supporting biodiversity, nutrient cycling, water regulation, and pollutant degradation in terrestrial ecosystems (HAO, ET AL. 2014)

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5.1.2. Biomass productivity

Definition

Biomass productivity refers to the rate at which biomass, such as plant material, is produced in a given area over a specific period of time. It is an important measure of the productivity and sustainability of ecosystems, especially in the context of agriculture, forestry, and bioenergy production.

How to assess

ISO 14040 and ISO 14044 provide standards for life cycle assessment (LCA), which can be used to evaluate the environmental impacts of biomass production systems, including biomass productivity. Additionally, ISO 13065 provides guidelines for the quantification and reporting of greenhouse gas emissions related to the carbon content of biomass and biomass-based products.

Application context

The assessment of biomass productivity can be done initially to establish baseline data. Subsequent revaluations can be conducted in the short term or in the long term to track changes in biomass production over time. Monitoring biomass productivity is essential for understanding ecosystem dynamics, assessing the impact of land management practices, and making informed decisions for sustainable resource use.

Link between each function

The greater the accumulation of photosynthetically active biomass, the higher the reflectance of NIR radiation, and the lower the reflectance of red radiation, resulting in an increase in NDVI value (SMITH ET AL., 2017), which indicates a greater amount of chlorophyll and biomass of the crop.

Biomass productivity is linked to various ecosystem services essential for maintaining ecosystem health and functioning. High biomass productivity supports habitat and biodiversity regulation by providing resources for diverse species. Nutrient capture by plants contributes to nutrient cycling and supports soil organisms and plant growth. Organic matter storage and cycling facilitated by biomass productivity sustain ecosystem processes. Biomass production helps maintain soil structure for plant growth and supports water retention and infiltration, reducing runoff and promoting groundwater recharge. Additionally, biomass productivity plays a role in pollutant attenuation and degradation by absorbing and breaking down pollutants in the environment. Overall, biomass productivity is crucial for sustaining ecosystem resilience, biodiversity, and the overall balance of natural systems (DHARUMARAJAN ET AL., 2023).

5.1.3. Land surface temperature

Definition

Land Surface Temperature (LST) is the temperature of the Earth's surface as measured from a satellite or other remote sensing platforms. It represents the temperature of the topmost layer of the Earth's surface that interacts directly with the atmosphere.

How to assess

ISO 15927-4:2003 - Space data and information transfer systems – Sensor and data model for imagery - Part 4: Land Surface Temperature.

Application context

The frequency of reevaluation will depend on the specific objectives of the study, the temporal scale of the phenomena being studied, and the availability of resources for data collection and analysis.

Link between each function

Soil temperature influences both adsorption of water and nutrients by existing roots and affects future root growth. As soil temperature increases, root carbohydrate demands increase due to increased respiration and as the carbon sink strength of the roots increases.

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Soil temperature plays a crucial role in various soil processes and functions that are essential for ecosystem health and sustainability. Soil temperature influences the types of organisms that can thrive in a particular habitat, impacting overall biodiversity. It also affects the activity of soil organisms involved in nutrient cycling and decomposition, influencing nutrient capture for soil organisms and plants. The rate of decomposition of organic matter, essential for nutrient cycling and soil fertility, is influenced by soil temperature. Soil temperature fluctuations can impact soil structure through freeze-thaw cycles, affecting water retention, infiltration, and root growth for plants. Proper soil temperature regulation is important for maintaining adequate soil moisture levels. Additionally, soil temperature influences the rates of biogeochemical processes responsible for pollutant attenuation and degradation, making it essential for sustainable land management practices and conservation efforts aimed at maintaining healthy soil ecosystems and supporting biodiversity conservation (MIRCHOOLI, ET AL. 2020; HOLL, 2020).

5.1.4. Water holding capacity

Definition

Water holding capacity (WHC) refers to the ability of a material, such as soil, to retain water after it has been wetted. It is an important characteristic of soil that influences plant growth and nutrient availability.

How to assess

There are various methods and standards for measuring water holding capacity in soil. One commonly used method is the gravimetric method, which involves determining the weight of soil samples before and after they are saturated with water. The ISO (International Organization for Standardization) does not have a specific standard for measuring water holding capacity, but there are various national standards and methods used by agricultural and environmental organizations.

Application context

The evaluation of water holding capacity can vary depending on the specific needs of the study or application. Typically, water holding capacity can be evaluated at different timescales: Short-term evaluations of water holding capacity can be done periodically over weeks or months to monitor changes in soil moisture content and water retention capacity. Long Term: Long-term evaluations of water holding capacity are conducted over extended periods, often years, to understand the long-term effects of management practices, climate change, or other factors on soil water holding capacity.

Link between each function

When the temperature changes, things like evapotranspiration, soil moisture, and infiltration may also change. This controls the amount of groundwater recharge that occurs by adjusting the ratio of surface run-off to infiltration. Percentage of Holding capacity (WHC%) = (Vw/Vt) * 100, Vw is volume of water., Vt is total volume of saturated soil.

Water holding capacity is a critical soil property that influences various aspects of ecosystem functions and services. Adequate water holding capacity supports habitat and biodiversity regulation by providing a stable environment for soil organisms and vegetation. It facilitates nutrient capture by preventing leaching, thereby promoting efficient uptake by plants and soil organisms. Additionally, it enables the storage and cycling of organic matter through microbial activity, contributing to nutrient availability and organic carbon storage. Good water holding capacity helps maintain soil structure, supporting root growth and plant access to water and nutrients. It also enhances water retention, infiltration, and groundwater recharge, while acting as a filter for pollutant attenuation and degradation. Managing water holding capacity is essential for sustaining healthy ecosystems and maximizing their resilience and productivity (DHARUMARAJAN ET AL.. 2023).

In the context of SOM method the methodological steps followed are described below:

- Data Acquisition:
  - Utilize satellite imagery, preferably from Sentinel missions, spanning a considerable period.
  - Select study areas comprising rehabilitated mining quarries and nearby natural areas for comparison.
- NDVI/NDMI Calculation:

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- Compute NDVI/NDMI values for each pixel.
- Aggregate NDVI/NDMI values for both rehabilitated and natural areas over time.

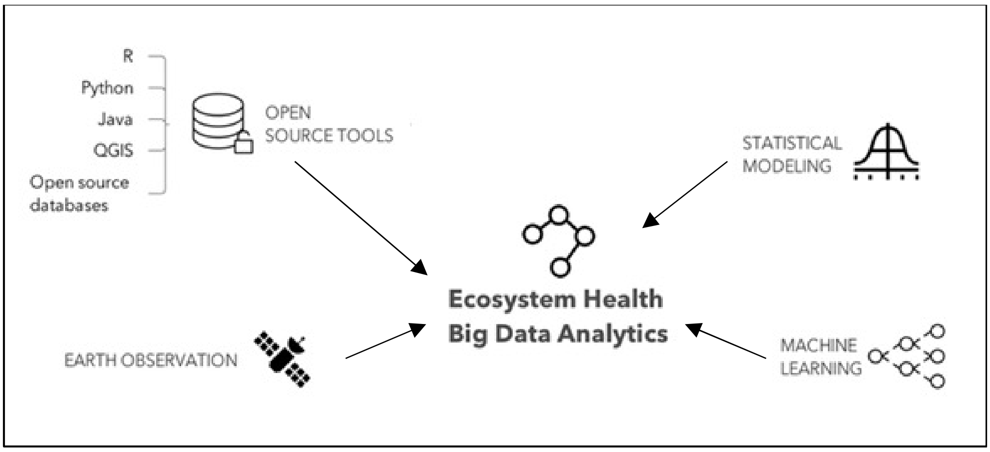

Figure 3. Overview of data source and analysis techniques

Self-organizing maps (or Kohonen netwroks) is an unsupervised machine learning technique (Kohonen, 1997). It is applied for data dimension reduction, to cluster complex data sets, to detect local data similarity and to identify patterns (Kohonen, 2013; Hsu and Li, 2010; Bowden et al., 2005; Richardson et al., 2003). SOM converts complex statistically based relationships of high-dimensional data to simpler spatial or temporal relationships which can be displayed as an easily interpretable map of a lower dimension. In a certain sense, SOM can be seen as a clustering technique, leading to identification of data groupings (clusters), i.e. points (vectors) in the training set. It is however different from the other clustering methods, which lead to attribution of each point to one of the cluster, like it is done e.g. by the widely used k-means clustering algorithm. SOM results in a set of nodes (arranged typically as a rectangular or hexagonal two-dimensional grid) which positions would be close (in terms of Euclidean distance) to concentrations (groupings) of data points. A trained SOM can subsequently be used as a classifer: it will classify a vector from the input space by finding the node (the so-called best matching unit, BMU) which is closest to this this input vector. Initially, the SOM nodes, forming a grid, are randomly located, and during the iterative training process would be gradually “moving” towards the concentrations of the data points. (The coordinates of nodes in input space are also called weights.)

In this study the two-dimensional rectangular SOM was employed to fill the gaps produced during image processing to calculate NDVI/NDMI. In this work, the SOM package (Wehrens & Buydens, 2007) was implemented. Self-Organizing Maps (SOMs) can effectively fill gaps in image processing. The basic idea is to leverage the unsupervised learning capability of SOMs to create a smooth representation of the input data, which can then be used to fill in missing or corrupted parts of an image. A simplified description of the approach is described below:

- Start by training the SOM using the available parts of the image. The SOM will organize the input data into a grid of neurons, preserving the topological relationships of the input space.
- Use only the non-corrupted parts of the image for training.
- Once the SOM is trained, use it to determine the most activated neuron for each pixel in the image. This is often referred to as the "winning neuron" or "best matching unit" (BMU).
- For the missing or corrupted parts of the image, find the BMU of the complete surrounding pixels.
- Assign the value of the BMU to the missing/corrupted pixel. This way, the gaps are filled based on the learned relationships in the SOM.
- Depending on the results, you can iterate through the process, retraining the SOM with the updated image and filling in the gaps again. This iterative refinement can enhance the quality of the filled image.
- Experiment with SOM parameters, such as the learning rate and neighborhood size, to achieve better results. These parameters can significantly influence the algorithm's performance.

Two performance indices can determine the quality and accuracy of the SOM results: the quantization and topographic errors. Quantization error is the average distance between the data vector and the best matching unit

(BMU) (the closest node). The quantization error shows how accurate the representation of the given input patterns by a BMU is. The smaller this index is, the better representation is. Topographic error is related to the quality of the map topology: it is assumed quality is high (so the error is low) if the nodes adjacent to each other on the grid correspond to similar input patterns (Beale & Jackson, 1990). It is calculated as the ratio of all of the vectors for which the first and second best BMUs are not adjacent on the grid.

An initial application was performed in the case study in Greece at Amyntaio area where SOM method was applied to estimate NDMI and NDVI form source satellite images.

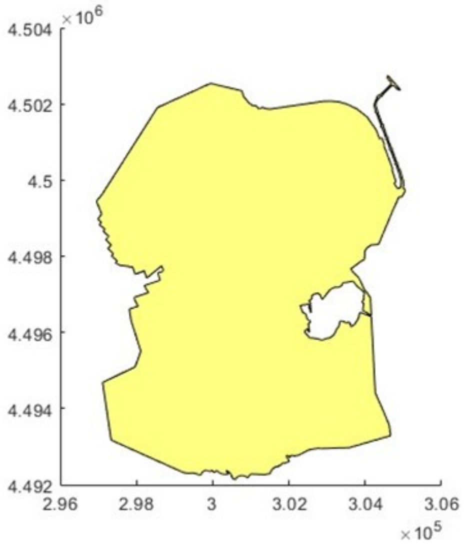

Figure 4. Amyntaion study area in Greece

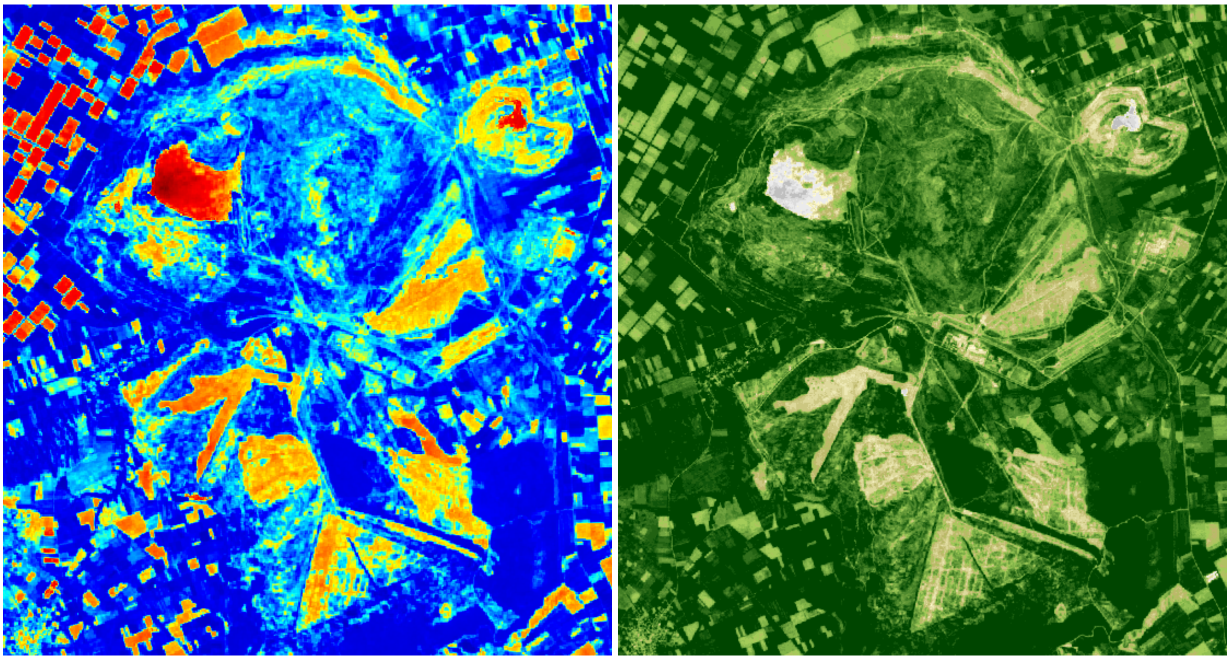

Figure 5. NDMI and NDVI calculation using SOM at Amyntaion study area in Greece

6. Conclusion

The evaluation and rehabilitation of soil ecological functions are crucial for the success of restoration efforts at mining sites. This document details the essential abiotic and biotic parameters necessary to understand the capacity of soils to fulfill their ecological functions. By combining small and large-scale measurements through on-site assessments, laboratory analyses, and remote sensing tools, we gain a comprehensive understanding of soil conditions and progress.

The methods and protocols detailed in this document provide a toolbox for the short and long-term evaluation and monitoring of rehabilitation efforts, thereby contributing to more effective and sustainable environmental management. The continuation of these efforts is indispensable for achieving the sustainable development and climate neutrality goals set by European institutions.

In conclusion, the comprehensive assessment and monitoring of soil ecological functions, as outlined in this report, will play a vital role in guiding and optimizing rehabilitation strategies for mining sites. These efforts will not only restore degraded landscapes but also enhance biodiversity, improve soil health, and contribute to the broader objectives of environmental sustainability and climate resilience.

Subsequently, these indicators will be deployed within the framework of the REECOL project for the assessment of ecological functions at various experimental sites. Following this, the methods for interpreting and referencing the selected indicators will be defined.

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