



**Politecnico
di Torino**



UNIVERSIDAD
POLITÉCNICA
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Politecnico di Torino

*Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle
Infrastrutture*

Master of Science Course in Environmental and Land Engineering:
“Industrial Environmental Sustainability”

Master of Science Thesis

Soil Quality Assessment in European Mining and Quarrying: a Novel Tiered Approach

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October 2025

Table of Contents

Executive summary	3
1 Introduction	1
1.1 Role and Nature of Soil	1
1.1.1 Structure of soil	4
1.1.2 Physical properties of soil	5
1.1.3 Chemical properties of soil	11
1.1.4 Biological properties of soil	15
1.2 Soil Quality in the European Union	16
1.2.1 Directive on Soil Monitoring and Resilience (COM, 2023)	19
1.3 Mining and Quarrying	20
1.3.1 Mining environmental impacts	22
1.3.2 Soil Degradation in Mining Areas	23
1.3.3 Mine Soil Definition	24
1.4 Objective of the thesis	28
2 Materials and Methods	30
2.1 General Overview of the SSHCMP	30
2.1.1 Module I: Soil characterization and diagnosis	32
2.1.2 Module II: Measures to protect and maintain soil quality	35
2.1.3 Module III: Rehabilitation and restoration of mining soils	39
2.2 Soil Quality Evaluation System	42
2.2.1 Soil descriptors selection	44
2.2.2 Soil function scoring	48
2.2.3 Algorithm description and flowchart	52
2.3 Testing of the model	55
2.3.1 Comparison of Natural and Degraded Soils (Tier 1)	56
2.3.1 Comparison of Tier 1 vs Tier 2 results	59
2.4 Data and document sources	60
2.4.1 Data preparation	62
3 Results and Discussion	68
3.1 Natural and degraded soils results	68

3.1.1	Dicussion and use of the model	72
3.2	Tier 1 vs Tier 2 results	75
	Conclusions	79
	References	81
	Annex A – Descriptors value ranges corresponding to each score level	87
	Annex B – Single Flowcharts for each of the seven functions	90

Executive summary

This thesis was developed within the framework of the Soil Survey and Health Conservation Management Plan (SSHCMP), the methodological guide proposed by the European ROTATE project for the sustainable management of soils in mining and quarrying sites. The work focuses on the application and testing of a functional soil quality assessment model, designed to evaluate the ecological condition of soils throughout the entire mining cycle, from pre-extraction to post-rehabilitation.

The evaluation system is based on seven soil functions and is structured in two tiers of application: Tier 1, which uses only topsoil data, and Tier 2, which incorporates information from the full soil profile. The thesis presents a detailed methodology for selecting descriptors, calculating function scores, and interpreting results. The model was tested using a combination of natural soils from European datasets (LUCAS and ESDAC) and contaminated soils from a former arsenic–copper mine in northern Spain. Comparisons were carried out to evaluate both the model's capacity to detect differences between natural and degraded soils and the consistency between Tier 1 and Tier 2 outputs.

The results show that Tier 1, despite its simplified nature, provides coherent and conservative results when compared to Tier 2. The model successfully identified key differences in soil functionality between degraded and non-degraded contexts, confirming its potential as a tool for diagnosis, monitoring, and support to decision-making in soil restoration efforts in mining environments.

1 Introduction

Mining and quarrying activities are one of the main drivers of soil degradation in Europe, leading to the loss of soil functions, reduced biodiversity, and long-term environmental impacts. As the European Union increases its focus on soil protection and restoration, it becomes crucial to understand how these activities affect soil quality and what measures can be implemented to monitor and mitigate their impacts. This chapter aims to explore the current state of soils in Europe, especially in mining areas and evaluate them within the framework of recent EU policies, such as the recently proposed Directive on Soil Monitoring and Resilience (Soil Monitoring Law). The following sections include a general description of soil, its degradation in the context of extractive industries, and the main objectives of soil restoration and monitoring in these disturbed environments.

1.1 Role and Nature of Soil

Soil is a natural resource that plays a crucial role in maintaining ecosystems and providing various essential services for humanity, shaping the landscape and serving as a substrate for vegetation (FAO and ITPS, 2015). Together with air and water, it is an essential natural resource that supports a range of ecosystem goods and services for humankind. Its value lies not only in its productive function (perhaps the most widely recognized) but also in other inherent services, such as carbon sequestration, water purification, aquifer recharge, pathogen control and biodiversity conservation (Laishram, 2012). For example, the amount of carbon contained in soil is approximately twice the amount found in the atmosphere and three times that in vegetation. These functions are worthy of protection due to their socioeconomic and environmental importance. These multiple services play a fundamental role in climate regulation, food production, and the provision of habitats and natural resources. Soil is also a living medium with high biodiversity, where biological activity helps determine soil structure and fertility, which is essential for it to perform some of its functions. Alongside water and air, soil is considered the third environmental component, as countless forms of life develop in or on it. The importance of soil lies in its numerous environmental, economic, social, and cultural functions,

making it one of the most important natural resources on Earth (Ballesta, 1998). Unlike air and water, soil is typically subject to property rights.

Although most people have a general understanding of what soil is, various organizations have proposed complementary definitions. For example, three similar but distinct definitions are provided below:

- *“Soil is a natural body consisting of layers (soil horizons) that are composed of mineral constituents, organic materials, air, and water. It serves as a natural medium for plant growth and provides essential ecosystem services such as water filtration, carbon storage, and habitat for organisms.”* (FAO & ITPS, 2015)
- *“Soil is the unconsolidated mineral or organic material on the immediate surface of the Earth that serves as a natural medium for the growth of land plants. It is a dynamic natural body that supports life, regulates water, and cycles nutrients.”* (Brady & Weil 2016)
- *“Soil is a complex, heterogeneous system composed of mineral particles, organic matter, water, air, and living organisms. It functions as a critical interface between the atmosphere and lithosphere, supporting plant growth and regulating biogeochemical cycles”.* (Smith et al., 2015)

One of the most widely used describes soil as the upper layer of the Earth’s crust. Generally speaking, soil is a natural, organized, and independent entity whose constituents, properties and formation are the result of the action of a set of factors (climate, living organisms including humans, topography, time, geology, etc.) on a passive material such as bedrock. From an economic and geological perspective, soil is considered a finite and non-renewable resource due to the extremely slow process of its formation. It takes over 1,000 years to generate just 1 to 3 centimeters of top soil, meaning that its conservation is of great importance. However, its rate of degradation is relatively rapid, and being soil a complex medium, it is very fragile to external aggression (Jones et al., 2012)

The European Commission document “Towards a Thematic Strategy for Soil Protection” (COM 2002, 179) defines its main functions as follows:

- it is a source of food and biomass production.
- it plays a major role in water protection and gas exchange with the atmosphere.

- it is the habitat for numerous organisms and plays essential ecological roles.
- it serves as a base for human activities and is a key element of the landscape and cultural heritage.
- it is a source of raw materials.

Soil has the capacity to perform a series of essential functions in nature: environmental, ecological, economic, social, and cultural. It also provides the nutrients, water, and physical support required for plant growth and biomass production, playing a fundamental role as a source of food for living beings. Additionally, it serves as a platform for human activities by supporting socio-economic structures and is part of the landscape and cultural heritage.

In recent decades, the scientific community has adopted a more holistic approach to the concept of soil functions, assessing not only its productive capacity but also its role in human and social well-being (Bouma, 2014; FAO & ITPS, 2015; Greiner, 2017). This concept acknowledges that soils have various capabilities beyond their direct use and can perform multiple functions depending on their physical, chemical, and biological properties. The definition of soil function includes the idea that a specific type of soil must be capable of fulfilling its role within a natural or managed ecosystem, and that this multifunctionality is key to sustainability and human well-being (Karlen et al., 1997). The soil functions approach highlights the need to assess its role not only in terms of productivity but also in relation to the ecosystem services it provides, emphasizing the importance of healthy soils in maintaining ecosystem balance (Greiner, 2017). The concept of soil functions was adopted in the European Commission's Soil Protection Strategy (2006), which identified seven essential functions that soil must fulfill to support life and ecosystems. These include: (i) food and biomass production, (ii) compound storage and filtering, (iii) provision of habitats and gene pools, (iv) physical and cultural environment, (v) source of raw materials, (vi) carbon reservoir, and (vii) archive of geological and archaeological heritage. These functions underline the importance of soil not only in sustaining life but also in mitigating climate change and conserving biodiversity.

1.1.1 Structure of soil

In edaphology, a soil horizon is understood as a layer more or less parallel to the earth's surface, which presents physical, chemical, and biological characteristics distinct from adjacent layers (Figure 1). These layers form over time as a result of soil formation processes such as weathering, leaching, accumulation of organic matter, biological activity, and interaction with the climate (Laliberté et al., 2013).

Each horizon reflects a specific stage or component of the soil-forming process and possesses distinctive properties such as color, texture, structure, chemical composition, and organic matter content:

- Horizon O (Organic): Composed predominantly of organic matter in various states of decomposition. It is found in forest soils, wetlands, and areas with high accumulation of plant residues.
- Horizon A (Surface): A mixture of minerals with humified organic matter. It is the most biologically active and fertile horizon. It usually has a dark color due to humus content and is where much of the plant root activity occurs.
- Horizon E (Eluvial): Characterized by the leaching of clays, iron oxides, and organic matter. It appears lighter due to the loss of these materials.
- Horizon B (Subsurface or Illuvial): Accumulates materials leached from the upper horizons (clays, oxides, humus). It can be denser and have a reddish or yellowish color. This indicates the presence of accumulation processes or "illuviation".
- Horizon C (Parent Material): Little or not affected by pedogenetic processes. It consists of fragmented rock, sediments, or unconsolidated materials, forming the base upon which the soil develops, but not considered part of the soil itself.
- Horizon R (Bedrock): Solid, unaltered rock that constitutes the original substrate from which the parent material may derive, and which is not considered part of the soil.

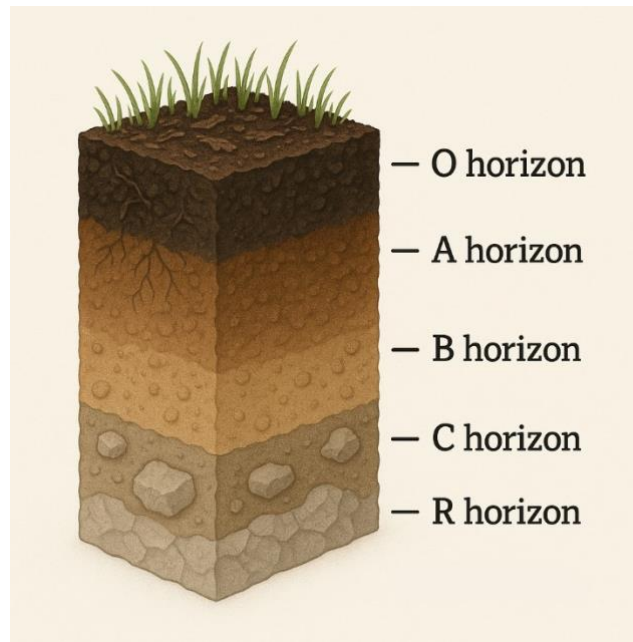


Figure 1 – Typical complete horizon structure of a soil

Not all horizons are always present in every soil, and intermediate horizons are often found, showing characteristics of two contiguous horizons, indicating a gradual transition between layers.

The study of soil horizons is fundamental in various fields because it provides key information about soil health, fertility, and capabilities. In particular, studying horizons is crucial for soil conservation, as it provides information on risks of erosion, compaction, or contamination that can affect the long-term quality and functionality of the land. Proper soil management based on this information is essential to ensure its sustainable use and to preserve natural ecosystems.

1.1.2 Physical properties of soil

Physical properties of soil play a fundamental role in its behaviour, use, and management. These properties largely determine the soil's capacity to retain water and nutrients, facilitate root development, allow aeration, regulate temperature, and resist erosion. Among them, structure, color, depth, temperature, texture, consistency, porosity, and density stand out, each providing key information about soil conditions and its suitability for various agricultural and ecological uses (Martín-Duque et al., 2015).

Soil Structure

Soil structure is the way in which the particles (both mineral and organic) that make up the soil bind together to form aggregates with their corresponding spaces between them (pores). The pores represent about 50% of the soil volume and act as channels through which water and air circulate and serve as habitat for soil fauna (Moore et al. 2022) Soil structure directly affects aeration, water movement within the soil, heat conduction, root growth, and resistance to erosion.

Soil Color

Color is usually the easiest property to characterize. Although it does not directly influence the behavior and use of soil, it can serve to indirectly assess some other properties (Brady & Weil, 2016). For example, it is used to differentiate sequences in a soil profile, evaluate drainage status, and detect the presence of salts, carbonates, and organic matter. Soil color depends on its solid components and varies with moisture content, organic matter present, and the oxidation state of minerals. The main substances that give soil its color are oxides, sulfides, sulfates, carbonates, and humus.

Black or dark color is due to organic matter. In fact, it is commonly accepted that the darker the surface horizon of the soil, the higher its organic content is assumed to be. If the dark color is irregularly localized in nodules or specific areas, it is attributed to the presence of iron and manganese compounds. White or whitish color is due to carbonates, gypsum, or more soluble salts. When found in eluvial horizons, it is reasonable to consider that there has been leaching of sands, composed mainly of quartz and possibly feldspars. Yellowish colors are attributed to hydrated iron oxides bound to clay and organic matter. Reddish colors are explained by the presence of ferric oxides such as hematite. Gray and reddish-brown colors indicate the presence of ferrous and ferric compounds. Greenish-gray and bluish colors correspond to ferrous compounds and clays saturated with Fe^{2+} .

Soil Depth

The effective depth of a soil is the space in which the roots of common plants can penetrate without major obstacles, with the aim of obtaining the essential water and

nutrients. Such information is of great importance for plant growth. Most plants can penetrate more than one meter, if soil conditions allow it.

As described by Agriculture U.S.D. (2019), soils can be classified into four groups according to their effective depth (Table 1):

Table 1 – Soil depth classification

Soil Depth Classes	Depth [m]
Deep soil	> 1
Moderately deep soil	0.6 - 1.0
Moderately shallow soil	0.25 - 0.60
Shallow soil	< 0.25

Soil Temperature

Soil temperature is not a universal value and depends on a series of characteristics, such as color, slope, vegetation cover (bare soil heats up faster, while any additional layer over the soil that prevents evaporation reduces its temperature), compaction, texture (clay usually shows a higher thermal capacity compared to sand at equal water content and density), moisture, the presence of organic matter (which increases water retention and darkens the soil, raising its temperature), and available sunlight.

High soil temperature regimes exhibit a greater cation exchange capacity due to decomposed organic matter. The warmer the soil, the more water-soluble phosphorus it contains for plants; conversely, cooler soils are poor in phosphorus (Onwuka, 2018). In turn, high temperatures cause dehydration and consequent cracking of particles. The higher the soil temperature, the greater the release of carbon dioxide; the soil cracks and reduces water infiltration in the soil profile. Temperature also influences vegetation distribution.

Soil Texture

Texture is one of the most stable and homogeneous properties and serves as a basic guide for determining each soil horizon. It is determined by the relative proportion of inorganic components of different shapes and sizes such as sand, silt, and clay. The interest in

knowing the particle size distribution lies in inferring other properties and characteristics directly related to soil use and behaviour, such as water circulation ease, risks of water and wind erosion, nutrient storage capacity, availability of water storage for plants and vegetation species, likelihood of surface crust formation, etc. Ultimately, it can be stated that texture influences soil fertility as a factor.

To separate the different particle size fractions (clay, silt, and sand), various organizations have proposed criteria, not always entirely consistent, to establish the boundaries between each. One of the most widely accepted corresponds to the definition by the United States Department of Agriculture (USDA) and the International Society for the Systems Sciences (ISSS) (Tables 2 and 3).

Table 2 – Common particle size classifications from USDA and ISSS

Particle Size Classes	USDA [mm]	ISSS [mm]
Gravel	> 2	> 2
Very coarse sand	1.0 - 2.0	-
Coarse sand	0.5 - 1.0	0.2 - 2.0
Medium sand	0.25 - 0.50	-
Fine sand	0.10 - 0.25	0.02 - 0.20
Very fine sand	0.05 - 0.10	-
Silt	0.002 - 0.05	0.002 - 0.020
Clay	< 0.002	< 0.002

Table 3 – Simple particle size classification from USDA

Particle Size Classes	USDA (Simple) [mm]
Sand	0.005 - 2.000
Silt	0.002 - 0.005
Clay	< 0.002

According to these criteria, the solid fraction is made up of sands, silts, and clays, represented in the texture triangle. Sands, with diameters from 50 to 2000 micrometers, constitute the coarse fraction of the soil. They give the soil a low moisture retention capacity, high drainage, low nutrient retention, low water supply capacity, excessive

aeration, susceptibility to surface crusting and erosion, ease of mechanical tillage, and so on.

Regarding silts, these are particles with diameters ranging between 2 and 50 micrometers. This fraction shows greater chemical and hydrodynamic activity than sand but less than clays. Soils rich in silts generally present good conditions for agricultural activity.

Finally, clays, with diameters smaller than 2 micrometers, provide the greatest physical, chemical, and hydrodynamic activity in soils. Soils rich in this particle size tend to have poor drainage.

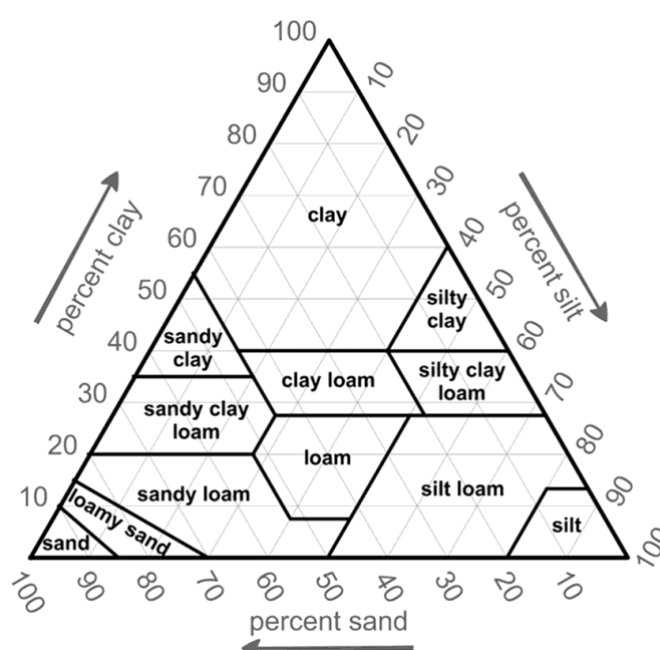


Figure 2 – USDA Soil Texture Triangle with twelve basic texture classes (Groenendyk et al., 2015)

Soil Consistency

Consistency is the property that defines the soil's resistance to deformation or rupture when force is applied. It is an important factor influencing soil workability and plant root penetration. Depending on its moisture content, soil consistency can vary widely, typically classified as hard, very hard, or soft. Therefore, it is measured based on a hierarchy of moisture conditions (air-dry, moist, and wet) since the soil's resistance changes significantly with its water content (FAO Training Series). This characteristic plays a crucial role in agricultural management, construction, and erosion control.

Soil Porosity

The soil's pore space refers to the percentage of the soil volume not occupied by solids (see Figure 3). In general, a standard and healthy soil volume consists of 50% solid materials and 50% pore space (Moore & Bradley, 2022). Within the pore space, based on diameter, macropores and micropores can be distinguished, where water, nutrients, air, and gases can circulate or be retained. Macropores do not retain water against gravity; they are responsible for drainage, soil aeration, and constitute the space where roots form. Micropores retain water, some of which is available to plants.

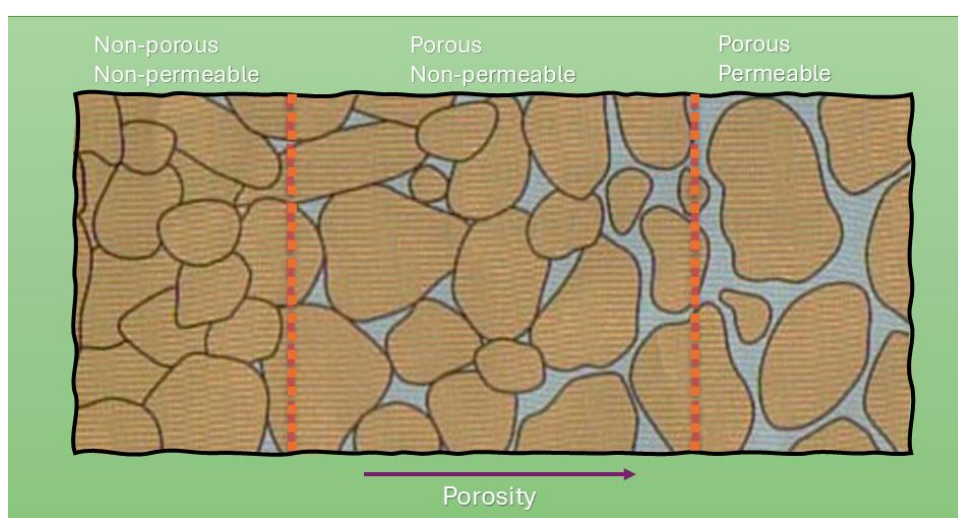


Figure 3 - Diagram illustrating soil porosity

Soil Density

Soil density is defined as the mass of soil per unit volume. There are two main types. Bulk density refers to the mass of a volume of dry soil, including both soil solids and pore spaces. Particle density refers to the mass of soil solids per unit volume of the solids alone, excluding pore spaces. Bulk density is typically measured in grams per cubic centimeter (g/cm^3) and it provides important information about soil compaction, porosity, and suitability for plant growth (Rai et al., 2017).

Electrical Conductivity

Electrical conductivity (σ) is the ability of an aqueous solution to conduct an electric current. It is a property of solutions that is closely related to the type and valence of the ions present, their total and relative concentrations, their mobility, the temperature of the

liquid, and its dissolved solids content. Therefore, measuring electrical conductivity is an indirect way to assess the salinity of water or soil extracts. According to the values of electrical conductivity, pH, and exchangeable sodium percentage, soils can be classified into the following categories (Porta Casanellas et al., 2008) (Table 4):

Table 4 – Types of soil according to their electrical conductivity

Soil Electric Conductivity Classes	Description
Saline soils	They are characterized because their saturation extract has an electrical conductivity value equal to or greater than 4 dS/m at 25 °C and the amount of exchangeable sodium is less than 15%. They usually have a crust of white salts, which may be chlorides, sulfates and carbonates of calcium, magnesium and sodium.
Sodic soils	They are black due to their high sodium content. Their exchangeable sodium percentage is higher than 15, the pH is between 8.5 and 10.0, and the electrical conductivity is below 4 dS/m at 25°C.
Saline-sodic soils	They have an electrical conductivity of 4 dS/m at 25°C, an exchangeable sodium concentration of 15% and a variable pH, commonly higher than 8.5.

1.1.3 Chemical properties of soil

Chemical characteristics are also varied and provide crucial information for assessing soil quality and condition (Daniels & Zipper, 2010). Among the most important are pH value, cation exchange capacity (CEC), organic matter content, the presence of macronutrients (Ca, K, S, H, C, O, N), and micronutrients (Fe, Cu, Zn, Mo, Co, Mn, B) (Brown & Gilkes, 2010).

Soil pH

Soil pH is a measure of the hydrogen ion concentration in the soil solution and reflects whether a soil is acidic, neutral, or alkaline. Soil pH significantly influences nutrient availability, microbial activity, and the chemical behavior of soil constituents (Brady & Weil, 2016). The pH value ranges from 0 to 14, with pH = 7 indicating a neutral soil reaction. Values below 7 indicate acidity, while values above 7 indicate alkalinity. The further the measurement is from the neutral point, the greater the acidity or alkalinity. It is the main indicator of nutrient availability for plants, influencing the solubility, mobility, and availability of nutrients as well as other inorganic constituents and

contaminants present in the soil. Soil pH values typically range from 3.5 (ultra-acidic) to 9.5 (very strongly alkaline) (see Table 5). Very acidic soils (<5.0) tend to have elevated and toxic amounts of aluminum and manganese. Similarly acidic values are identified in soils affected by coal mining (Mukhopadhyay et al., 2016; Roberts et al., 1988). The activity of soil organisms is inhibited in very acidic soils, and the ideal pH value for agricultural crops is around 6.5. Soil pH can vary if chemical reactions occur among its components. For example, pH variations from 8 to 3 have been observed due to pyrite oxidation, or conversely, an increase in pH after carbonate dissolution (Sheoran et al., 2010).

According to the USDA, soils can be classified according to pH as shown in Table 5:

Table 5 – Types of soils according to their pH (USDA)

USDA Soil pH Classes	pH
Ultra acidic	< 3.5
Extremely acidic	3.4 - 4.4
Very strongly acidic	4.5 - 5.0
Strongly acidic	5.1 - 5.5
Moderately acidic	5.6 - 6.0
Slightly acidic	6.1 - 6.5
Neutral	6.6 - 7.3
Slightly alkaline	7.4 - 7.8
Moderately alkaline	7.9 - 8.4
Strongly alkaline	8.5 - 9.0
Very strongly alkaline	> 9.0

Cation Exchange Capacity

Cation Exchange Capacity (CEC) is the measure of a soil's ability to retain positively charged ions (cations) such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+). These ions are held by electrostatic forces on the surfaces of soil particles, primarily clay minerals and organic matter. CEC is a key indicator of soil fertility (Table 6), as it determines the availability of nutrients to plants (Mukhopadhyay et al., 2016).

Table 6 – Types of soils according to their Cation Exchange Capacity (CEC) level

CEC level	CEC (meq/100 g)	Description
Very low	<5	Very low nutrient holding capacity indicating sandy soils with little or no clay or organic matter. Nutrients are easily leached.
Slightly low	5 - 10	Slightly low nutrient capacity indicating a clay mineral soil.
Normal	10 - 20	Suitable for high nutrient retention capacity indicating soils that tend to increase clay content.
High	> 20	Very high levels are normally found in very heavy soils with a high clay content or with a high level of organic matter. Nutrients may bind strongly to soil particles and availability may be restricted.

Organic Matter

In most soils, the percentage of organic matter is small and varies over time, but its effects on the physical and chemical properties of the soil are significant, although they depend largely on temperature and moisture conditions. Organic matter provides energy and components for most soil organisms (Brady & Weil, 2016) and is widely accepted as one of the main agents responsible for soil fertility.

According to Bradshaw & Chadwick (1980), organic matter content facilitates rehabilitation processes in soils altered by mining activity, as it helps retain water, enhances cation exchange capacity, and reduces compaction (Arranz-González, 2011). Table 7 shows the levels of organic matter in soil.

Table 7 – Organic matter (OM) critical levels in soils

Critical levels of OM	% OM
Low	< 1.5%
Medium	1.5 - 3.0 %
High	> 3%

Nutrient Content

The nutrient richness of a soil is determined by the availability of nutrients to be absorbed by plants. The 16 essential nutrients for plant development and growth are generally classified into macro- and micronutrients depending on the amount required by plants. Macronutrients are required in large quantities and include Carbon (C), Hydrogen (H), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), and Sulfur (S). Micronutrients, on the other hand, are needed in smaller quantities, although deficiencies can lead to nutrient shortages and excesses can cause toxicity. These include Iron (Fe), Zinc (Zn), Manganese (Mn), Boron (B), Copper (Cu), Molybdenum (Mo), and Chlorine (Cl) (Marschner & Rengel, 2023).

The biogeochemical cycles of phosphorus (P) and nitrogen (N) are particularly relevant, as they are among the key factors determining plant growth. In this regard, the EU Directive on Soil Monitoring and Resilience, which considers nutrient excess as one of the main indicators of soil degradation, focuses primarily on the presence of these two elements.

- **Nitrogen:** Most of the nitrogen in soil is present as part of organic molecules; therefore, its distribution is closely linked to the distribution of soil organic matter. Nitrogen is essential for the plant growth cycle. In plants, it combines products of carbohydrate metabolism to form amino acids and proteins. As a fundamental component of proteins, nitrogen is involved in all major plant development processes and is critical for yield production. The levels of nitrogen availability in soils are described in Table 8 (Castro & Gómez, 2013).

Table 8 – Critical levels of N in soil

Availability levels	% N total
Very Low	< 0.1 %
Low	0.10 - 0.15 %
Medium	0.15 - 0.25 %
High	0.25 - 0.30 %
Very High	> 0.3 %

- **Phosphorus:** Among nutrients, phosphorus ranks second only to nitrogen in its impact on the productivity and health of terrestrial and aquatic ecosystems. The total

amount of phosphorus in most native soils is low, and most of the phosphorus present is in forms that are not available to plants. It is essential for photosynthesis and other chemical-physiological processes. The levels of phosphorus availability in soil are described in Table 9 (Castro & Gómez, 2013).

Table 9 – Critical levels of P in soil

Availability levels	P [mg/kg]
Very Low	< 10
Low	10 - 20
Medium	20 - 40
High	> 40

1.1.4 Biological properties of soil

Soil organisms play a crucial role in nutrient cycles as they directly participate in the dynamics of soil organic matter, carbon capture, and modification of the soil's physical structure. In a way, it can be said that their involvement is fundamental in regulating the water regime and in the proper absorption of nutrients by vegetation. In fact, some of the microorganism's present help break down organic matter and transform nitrogen, phosphorus, potassium, and sulfur into forms more readily accepted by plants, in a process known as humification. Soil fauna is very diverse, and so are their effects on the soil; for example, nematodes and earthworms may affect plants but benefit soil structure.

Having described the soil's physical, chemical, and biological properties, the next goals are to understand the regulations and laws available for its protection, review the main impacts that mining can have on these properties, and explore methodological proposals for its preservation and rehabilitation.

The properties listed above are affected during mining activities, as these cause soil compaction with loss of structure, chemical deficiencies, anomalies in pH values, and reductions in biodiversity and organic matter content due to the removal of vegetation cover. This impact is inevitable because extracting minerals from deep deposits requires altering the natural environment (Wheeler & Miller, 1990). In modern society, the extractive industry plays a strategic role as a supplier of basic raw materials to other industries, so supply issues with these mineral raw materials can affect industrial operations (MITECO, 2022). However, the major challenge, based on best practices in

extraction, is to balance mineral benefits with the protection, remediation, and restoration of the soil (Banning & Murphy, 2008).

To evaluate soil quality status, it is necessary to establish and monitor various indicators. These are crucial to assess soil health and its capacity to perform essential life-supporting functions and are divided into categories including physical, chemical, and biological aspects. Physical indicators include soil texture, structure, and density, while chemical indicators focus on nutrient availability, pH, and the presence of contaminants such as heavy metals. Biological indicators include microbial biodiversity and biological activity that influence soil regeneration and fertility. Continuous monitoring of these indicators is fundamental to implementing management practices that ensure the long-term preservation of soil functions.

Despite its sensitivity and slow formation, soil health can be maintained or even improved through the implementation of appropriate measures. In fact, soil health directly contributes to achieving various Sustainable Development Goals (SDGs), especially SDG 15, which aims to combat desertification, restore degraded land and soil, and achieve land degradation neutrality by 2030. Healthy soil is also crucial for climate neutrality, reversing biodiversity loss, and ensuring food security, as it underpins long-term agricultural production. Moreover, healthy soil supports a green and circular economy and protects human health by preventing water and air contamination.

1.2 Soil Quality in the European Union

Soil quality is a fundamental component of environmental sustainability, agricultural productivity, and ecosystem health. In the European Union (EU), soils are critical for food production, biodiversity, carbon sequestration, and water regulation. The European Commission's Joint Research Centre (JRC), through the EU Soil Observatory (EUSO), reports that approximately 61% of soils in the EU are unhealthy, with only 39% classified as healthy.

Across Europe, soil degradation is currently caused by the following factors:

- **Compaction:** Pressure from heavy machinery or intensive grazing reduces soil porosity, affecting its ability to absorb water and promoting erosion.

- **Erosion:** Although a natural process, human activity accelerates erosion, leading to loss of soil function and damage to aquatic ecosystems.
- **Contamination:** The introduction of pollutants into the soil, either from point sources (such as mining or landfills) or diffuse sources (such as agriculture and atmospheric deposition), impacts both human health and ecosystems.
- **Loss of organic matter:** Agricultural and forestry activities, especially intensive practices, reduce the amount of organic matter in the soil, decreasing fertility and resistance to erosion.
- **Salinization:** The accumulation of salts, especially in irrigated lands in arid areas, lowers soil fertility and affects its capacity to support vegetation.
- **Soil sealing:** The construction of infrastructure covers the soil, preventing key functions such as rainwater absorption and contributing to ecosystem fragmentation, which is practically irreversible.
- **Biodiversity reduction:** The loss of soil organisms, essential for fertility, increases vulnerability to degradation processes such as erosion.
- **Natural disasters:** Floods and landslides worsen erosion and resource loss, severely affecting agricultural lands and ecosystems, especially in vulnerable areas

Soil degradation is a problem that affects every country, including all EU member states, even if the level of damage is different in each territory. When soil quality declines, it can cause serious problems for people's health, the environment, the economy and society. It can lead to food and water insecurity, make droughts and floods more dangerous and increase the loss of biodiversity and vegetation. It also causes more carbon to be released into the atmosphere, which contributes to climate change, social instability and migration.

The European Soil Charter (Council of Europe, 1972) marked the beginning of Europe's concern about soil degradation and contamination caused by human activities. Since then, the European Commission has adopted various strategies, plans, and legislation aligned with the proper management, protection, and recovery of soil. Some of the most relevant are the following:

- **World Soil Charter (FAO, 1982):** Adopted at the 21st FAO Conference in November 1981 and published in 1982, the World Soil Charter establishes fundamental principles for the optimal use, conservation, and enhancement of soil productivity.

It highlights the essential soil functions, including agricultural productivity, water conservation, climate regulation, and biodiversity support.

- EU Thematic Strategy for Soil Protection (European Commission, 2006): Presented through Communication COM (2006) 231 within the framework of the Sixth Environmental Action Programme, this strategy addresses threats identified since 2002, such as erosion, loss of organic matter, contamination, salinization, compaction, biodiversity loss, sealing, landslides, and flooding. It emphasizes these threats as primary risks to soil structure and function
- EU Soil Strategy (European Commission, 2021): Published on 17 November 2021 under the title “EU Soil Strategy for 2030: Reaping the benefits of healthy soils for people, food, nature and climate,” this strategy focuses on soil health and ecosystem services. It promotes the increase of soil organic matter, restoration of degraded soils, reduction of sealing and erosion, and the introduction of a future “Soil Health Law.”
- “A Soil Deal for Europe” EU Mission: EU Missions are a way to provide concrete solutions to some of the greatest challenges by 2030 within the Horizon Europe framework. The EU Mission for Soil aims to promote healthy soil by 2030 through the creation of 100 living labs and lighthouses. This initiative highlights the crucial role of soil in supporting life, food systems, clean water, biodiversity, and climate resilience.

Although current EU policies have positively contributed to improving soil health, there are currently no harmonized data on soil health derived from soil status monitoring. Member States use different sampling methods, indicators, and analyses, resulting in a lack of consistency and comparability within the EU. To address this issue, the European Union has adopted a comprehensive approach to confront soil degradation problems through two main regulations such as the Nature Restoration Regulation (EU) 2024/1991 and the new proposal for the Soil Monitoring and Resilience Directive (COM, 2023) 416 final. In Section 1.2.1, a detailed description of the Directive on Soil Monitoring and Resilience is provided, as it serves as the foundational document for the soil quality evaluation system developed and applied in this thesis, which will be presented in detail in Section 2.2.

1.2.1 Directive on Soil Monitoring and Resilience (COM, 2023)

The proposed Directive on Soil Monitoring and Resilience introduces a common legislative framework with the long-term goal of achieving healthy soils across the EU by 2050.

The Directive is built around several key objectives aimed at ensuring sustainable soil management and protection throughout Member States:

- Establish a solid and coherent soil monitoring framework.
- Address all aspects of soil degradation.
- Achieve the aspirational goal of healthy soils by 2050.
- Guarantee the provision of ecosystem services focusing on:
 - Environmental, social, and economic needs.
 - Climate change, biodiversity, resilience, including improving resistance against natural disasters, ensuring food security, and protecting human health.

One of the fundamental pillars of this Directive is the creation of a harmonized soil monitoring system based on standardized procedures for sample collection, analysis of key parameters, and assessment of soil health status throughout the territories of the Member States.

To implement this, the Directive establishes the need to define soil units and soil districts, conceived as homogeneous entities in terms of soil type and land use. Based on this, a geostatistical sampling plan must be designed to ensure adequate representativeness, allowing reliable characterization of soil status in each unit. This facilitates the monitoring of soil evolution and identification of critical areas requiring intervention.

For consistent evaluation of soil health, the Directive defines a minimum set of common soil descriptors (e.g., organic carbon content, bulk density, compaction, water retention, presence of contaminants, etc.) with harmonized quantitative criteria. While Member States may adjust some thresholds based on specific conditions, they must operate within a common methodological framework that guarantees data comparability across the EU.

Analytical quality and data interoperability are strengthened by requiring that laboratories involved comply with recognized quality management systems. Additionally, the Directive envisions the development of a European digital data portal on soil health, centralizing and standardizing data access collected by Member States. This portal will support research, environmental management, and land-use planning, thereby making soil health a tangible and comparable indicator across the EU. This integration also enhances the alignment of soil protection with other EU policies, including agriculture, climate, and biodiversity.

Monitoring and assessment responsibilities are allocated to competent authorities within the defined soil districts and units. Methodologies for sample surveys and descriptor analyses are standardized to ensure reliable data collection. The EU supports these efforts through initiatives such as the LUCAS soil survey and the Copernicus program, which provide detailed and accurate soil information. Monitoring will be conducted in regular cycles, accompanied by mandatory reporting to ensure transparency and facilitate informed decision-making to promote sustainable soil management.

Finally, in the specific context of mining and quarrying, the Directive emphasizes the importance of coordinating soil protection measures with broader EU strategic goals, particularly the secure and sustainable supply of critical raw materials. This ensures that soil resilience and protection are integrated coherently within extractive industry activities, minimizing environmental impacts while supporting European industry needs.

1.3 Mining and Quarrying

Mining is one of the oldest human activities. Since the Paleolithic era, humans have extracted rocks to make tools for their survival (Kogel, 2013) . Therefore, it can be said that the development of mining has evolved alongside humanity itself. Today, practically all the objects we use (appliances, means of transport, housing, medicines, among others) require minerals or industrial rocks.

Mining, as an industrial activity, consists of the selective and profitable extraction of mineral resources present in the Earth's crust. Mining and quarrying both involve the extraction of minerals from the earth, but they differ primarily in the type of material

extracted and the method of extraction. Mining typically refers to the removal of valuable minerals or metals from deep underground or open pits, often involving extensive tunneling or shafts. It targets ores and minerals that require processing to extract metals or fuels. In contrast, quarrying is the extraction of non-metallic minerals such as stone, sand, gravel, and other construction materials directly from the earth's surface, usually through open-pit operations open to the sky. Quarries generally produce materials used as-is, like building stone or aggregates, whereas mining often involves further processing of the extracted material (for example: iron to steel) (The Institute of Quarrying, 2025; CMQ Engineering, 2025; Tiruta-Barna et al., 2017). Some examples of open-pit extraction activities, which are among the most environmentally damaging forms of mining, particularly in terms of soil degradation and landscape alteration, are presented in Figure 4. It illustrates different types of open-pit operations and highlights their visible impact on the terrain, due to the large scale removal of soil and rock layers to access the desired resources near the surface.



Figure 4 – Open-pit mining examples (López Jimeno, 2020)

In recent years, global economic growth has significantly increased the demand for mineral raw materials, reinforcing the strategic role of this activity, especially in the field of metallic mining, which has seen considerable expansion. This growing demand for energy, minerals, and metals has caused significant alterations to the Earth's surface. Modern society, with greater environmental awareness, demands that disturbed areas be regenerated for sustainable use, making the abandonment of contaminated mining and quarrying sites unacceptable.

1.3.1 Mining environmental impacts

The environmental impact of underground mining is generally less severe than that of surface mining. In broad terms, mining and quarrying activities typically cause environmental impacts on soil, air, and water resources, as well as on their biotic components. Additionally, impacts may occur on nearby human populations due to dust inhalation or effects caused by contaminated soils (Bell & Donnelly, 2006). These impacts (atmospheric, hydrological, edaphic and landscape-related) will be discussed here, emphasizing those aspects directly or indirectly linked to soil quality.

Atmospheric impacts stem from the emission of solid particles, gases, and noise. Solid particles originate from blasting operations used to open or prepare mining and quarrying fronts, as well as from internal transport within the mine or quarry of extracted minerals, rocks, or waste material. While the most significant implications are those affecting workers' health, an excess of these particles can also harm plant growth. To minimize this negative effect, revegetation of temporarily or permanently abandoned areas must be carried out. This revegetation requires knowledge of the soil quality where it will take place.

Another possible impact of mining and quarrying is on the landscape. Extractive activities alter the original morphology of the terrain, creating slopes and even vertical walls. This changes the original soil and its vegetative cover. Furthermore, the removal of large volumes of waste material requires storage, occupying land areas that, due to lower cohesion, are prone to erosion and displacement by water or wind.

Regarding hydrological impacts, mining and quarrying activities can induce modifications in surface watercourses, resulting in changes to the water balance due to altered infiltration and runoff caused by changes in soil and vegetation. To address this issue, the establishment of vegetative covers adapted to soil conditions will be necessary. In all these cases, soil evaluation is essential.

Finally, edaphic impacts are the most significant. Soils resulting from mining and quarrying operations are composed of a variable and heterogeneous mix of residual materials, mine waste, etc., that are not adapted to the original characteristics of the area prior to the start of extractive activities. These altered soils present major challenges for the development of plant species.

1.3.2 Soil Degradation in Mining Areas

Soil plays a key role in restoring vegetation in areas damaged by open-pit mining. This topic is especially important today, as Europe is going through an Energy Transition and needs many minerals, which are considered critical raw materials, for producing new technologies. Because of fast innovation and growing economies, the demand for these minerals is increasing and it is expected to double by 2030 compared to 2010.

Right now, Europe still depends on importing critical raw materials (CRM) from other parts of the world, because local sources are not enough. This new interest in mining also brings more concern about protecting the environment and preserve landscapes among the public society.

Even if extracting minerals and rocks is necessary for society, open-pit mining has a strong impact on the environment (Martínez-Ruiz & Fernández-Santos, 2001). It changes the shape of the land, removes the natural vegetation and soil, and affects animals living there. These actions damage the balance of ecosystems that took a long time to form. Mining can also change water flows, increase flooding risks and cause pollution in rivers and underground water (Valladares et al., 2017). This type of exploitation not only changes the landscape but also deeply affects natural water flows (Arranz-González, 2004). That is why good land management is very important before starting any extraction work, to avoid damaging the area. When the mining activity ends, it is also important to cover the site with a layer of soil that has the right properties and thickness, so that plants can grow again. Both aspects, pre operational and post operational, are key to successful restoration.

However, even if the work is planned carefully, the soil in mined areas usually has many problems, like excessive compaction, poor chemical balance, low fertility, and drainage issues. All of these make it harder for plants to grow again unless the soil is treated first (IGME, 2001).

When an open-pit mine or quarry closes, different things can happen. Sometimes the site is just left with empty pits, very steep rock walls, or piles of leftover material. Other times, artificial soils are created by adding layers of soil, crushed rock, which is often called “mine soil” (Arranz-González, 2011). A big issue is that it’s not always possible to completely restore the surrounding environment, because it depends on the type of

material that was taken out. In some cases, it's possible to rebuild the soil and vegetation using leftover materials, but this is often not an option in quarries for ornamental stone or aggregates, which are usually left as flat areas surrounded by high rock walls, which is not suitable for future land uses, whether for natural restoration or for artificial purposes (Arranz-González, 2004; Martin-Duque et al., 2010; Solé Benet, 2024).

In these situations, it is very important to prepare the land before the establishment of vegetation. It is necessary to identify and implement effective solutions to overcome the limitations of the existing substrate. For example, the soil needs good drainage, enough nutrients, the right pH level and potentially toxic elements should be removed. Additionally, the soil layer must be deep enough for the intended use, and the land must not be compacted, to allow roots to grow freely and deeply.

However, soil quality assessment and its potential for use are often carried out on large scales, from regional to national levels. Since there are not common rules at the European or international level, it's hard to choose which indicators to use and how to interpret the results. This generates uncertainty and makes it difficult to compare soil data from different places in a consistent way.

1.3.3 Mine Soil Definition

Mine soils are those that have been modified, altered, or degraded by activities related to mineral extraction. In other words, they consist of any type of covering material (subsoil, mine waste, etc.) that remains on the surface of a mining or quarrying site as a medium for vegetation growth (López Jimeno, 2020).

As the life cycle of mining and quarrying activities progresses, especially upon their conclusion, the physical, chemical, and biological properties of natural soils become compromised, resulting in an environment conditioned by human activity (Tsolova et al., 2014). The new soil formed is a mixture of layers from the original soil, although not necessarily from the same location, combined with fragments of excavated rock. In most cases, these new surfaces are colonized by vegetation spontaneously or are revegetated to initiate soil formation.

It can thus be stated that in extractive industry areas, mineral resources coexist with natural resources such as water bodies and natural soils. One outcome of these activities is the formation of a specific type of soil characterized by human influence: mine soil. These soils result from the interaction between the original natural soil before the start of mining and quarrying, the mining waste, and the extractive operations (excavation, loading, transport, processing, etc.).

It is important to note that the characteristics of mine soils are not homogeneous; they depend on the properties of the original soil prior to alteration, the type of mining or quarrying operation, and more specifically, the type of mineral extracted. A fundamental characteristic of these soils is the presence of highly variable features in their profiles that depend on the geological materials mobilized during the mining phase, as well as the mining practices used (Pellegrini et al., 2016). Therefore, mine soil originates from any kind of mining-related material (surface layers, subsoil, waste rock, or any combination) deposited over the original geological or soil substrate.

Since the 1970s, there has been a trend to include mine soils as a distinct category within conventional soil classification systems. This change was significant, as before they were often considered merely as spoil heaps or mining waste. From the mid-1980s, the Soil Conservation Service of the U.S. Department of Agriculture (USDA) began defining soil series in mining areas and mapping phases of these series, which helped recognize mine soils as anthropogenic or anthropogeomorphic soils.

The WRB (2015) places mine soils within the Technosols group, characterized by properties and pedogenesis influenced by external technical factors intrinsic to mining and quarrying operations.

Most areas dominated by mine soils consist of coarse elements but also include fine particles, which may vary greatly in origin (mobile particles of various sizes, fragmented mineral material, variable water content, organic matter, and air) (Spangler, 1982). The formation of these soils may have been accidental, improvised, or rigorously planned through the dumping or spreading of fragmented or unconsolidated geological materials, soil layers, or both.

Some of the characteristics exhibited by these soils altered by mining and quarrying activities are presented below:

- **Altered texture:** Changes in texture (porosity, permeability) occur due to particle deposition processes, swelling, compaction, etc. Mining activities tend to cause particle size selection, resulting in homometric materials, with an abundance of coarse particles (>2 mm diameter). The abundance of coarse materials depends on the geological cover materials and the extraction processes at mining fronts and subsequent handling (transport and dumping of waste). The presence of coarse materials is generally seen as a limitation for plant species development, although some studies show that with appropriate restoration techniques (such as the inclusion of small volumes of sand), successful reforestation is possible (Limstron, 1960; Ashby & Vogel, 1994).
- **Altered structure:** The loss of colloidal components, especially organic matter, reduces or even eliminates biological activity, causing soil particles to lose aggregation and become loose, independent, or form massive blocks. Consequently, soil structure is affected by compaction, horizon mixing, particle deposition, among other processes. It is unlikely to retain a profile identical to the original; almost certainly, its position, thickness, and deeper layers will differ. This compaction is mainly caused by heavy machinery used in mining. Compaction reduces macroporosity, increasing root resistance, hindering infiltration, drainage, water and nutrient retention, and aeration. All these factors negatively affect the survival and growth of trees and other plant species (Pond, 2005).
- **Anomalous chemical properties:** Mine soils are characterized by extreme values in some chemical properties. They generally undergo intense and accelerated oxidation, which leads to a significant release of H^+ ions (most oxidation reactions acidify), drastically lowering soil pH (<3). Acidic conditions create a hyperacidic and hyperoxidizing environment, causing intense mineral attack. Ionic species typical of these environments appear, highly toxic to aquatic and terrestrial organisms (Al^{3+} , Fe^{2+} , Mn^{2+} , Pb^{2+} , Cu^{2+} , Zn^{2+}). In summary, these conditions make the environment unsuitable for organism development (Pérez et al., 2012)
- **Low nutrient content:** Removal of vegetation and the soil's top layer to access minerals exposes the underlying soil to wind and water erosion. This can lead to loss of fertile soil and reduce the land's ability to support plant life. Deficiencies are often identified in the most important biogenic groups (C, N, and P) due to

drastically reduced biological activity. Also, since the most biologically active topsoil horizons are removed during mining, biological activity is diminished (Quintas & Macias, 1992)

- **Depth:** Soil horizons are altered during stripping operations, sometimes mixing different horizons. Soil quality and homogeneity are reduced when depositing waste materials. Loss of topsoil horizons due to induced erosion may also occur. Soil depth is decreased, leaving only a thin layer after topsoil removal. This limits root development to a narrow surface layer, hindering growth (Arranz-González, 2004a).
- **Altered cation exchange capacity:** Low cation exchange capacity is identified, due to the scarcity of clay fractions and insufficient or poorly developed organic matter.
- **Low water retention:** Due to the lack of materials with adequate properties and the absence of soil structure, the soil's water regime varies because of the aforementioned texture and structure changes, as well as fluctuations in the water table (Marchevsky et al., 2018).
- **Presence of toxic compounds:** These compounds hinder rapid colonization of deposits. One of the most serious problems is contamination by heavy metals (Cu, Pb, Cd, Hg, etc.), metalloids (such as As), and hydrocarbons generated by liquid and solid effluents. Metal mobility and availability depend on soil characteristics, an important factor in contamination studies. Soils with higher clay content exhibit lower metal mobility due to adsorption, while sandy soils show less adsorption, allowing greater mobility to deeper layers (Ramírez Niño & Navarro Ramírez, 2015). For example, soils and materials associated with open-pit coal mining present problems of phytotoxicity due to high metal concentrations (Ghose & Kundu, 2004). These heavy metals reduce root respiration, water and nutrient supply, and inhibit cell division in root meristems (Arranz-González, 2004b; Clark & Clark, 1981).

In summary, mining activities cause intense modifications in soils that often lead to their destruction, leaving materials with severe limitations that usually require corrective measures to restore at least the original quality and properties of the soil before mining began. Since the physical, chemical, and biological properties of mining-affected soils are altered, as shown above, they often cease to be recognized as natural soils and are identified as mine soils.

The evaluation, monitoring, and control of the soil in areas where extractive activities occur must consider several aspects. First, the original natural soil existing before mining operations must be characterized. Then, the changes caused by mining operations such as mineral removal, internal transport, and subsequent treatment of extracted material must be recognized. During these phases, mainly physical properties (texture, structure, depth, etc.) are altered. Consequently, erosion phenomena and changes in the water regime may intensify, affecting plant species development. Mining involves mobilizing large soil volumes, changing structures, textures, and other properties, creating large pits, waste dumps, and artificial ponds, which ultimately alter the natural landscape relief. In a later phase, after waste deposition begins, soil effects may focus on heavy metal contamination, especially in metal mining and on structure.

If these mine soils are abandoned after mining activities end or even earlier, a process of evolution toward more mature soil forms will begin. The problem is they will not have the inherent characteristics of the original soil before mining, nor will they resemble soils in the same environment unaffected by mining. Greater soil homogenization can only be achieved by developing a rigorous methodology for characterization and control, the main objective of this study. Knowledge of the pre-existing natural soil and incorporation of materials from those soils will be necessary.

1.4 Objective of the thesis

The main objective of this study is to propose the development and critical evaluation of a tiered approach model for the preliminary assessment of soil quality in the context of mining and quarrying operations. The model aims to support the early stages of decision-making processes by identifying key soil parameters that influence restoration potential and ecological functionality.

This model is developed within the framework of the EU-funded ROTATE project (No. 101058651), which addresses several sustainability-related challenges in the extractive sector. In particular, the proposed methodology contributes to Goal 4 of the project, which focuses on the rehabilitation of mining sites and biodiversity management. The methodological guide associated with this goal seeks to ensure that soil physicochemical

and textural properties are preserved throughout extraction, handling, and rehabilitation phases.

The proposed guide corresponds to the Soil Survey and Health Conservation Management Plan (SSHCMP), and is structured into three modules:

- Module I: Soil characterization and diagnosis;
- Module II: Measures to protect and maintain soil quality;
- Module III: Rehabilitation and restoration of mining soils.

Through these modules, the SSHCMP establishes procedures and criteria to evaluate and preserve soil quality during the extraction, handling, and rehabilitation phases, ensuring that its physicochemical and textural properties do not undergo critical alterations.

This thesis focuses specifically on Module I, which introduces a structured approach for the preliminary assessment of soil health. It is within this framework that the proposed tiered evaluation model (Tier 1 and Tier 2) is developed, aimed at assessing soil quality through a set of physical, chemical, and biological indicators relevant to post-mining land restoration.

A key component of the study is the critical evaluation of this model, tested using real data from two main sources: a set of natural soils from various European regions (based on LUCAS and ESDAC datasets), and soils from an abandoned contaminated mining site in northern Spain, for which data were made available through previous studies (Serrano-García et al., 2025). The evaluation includes a comparison of soil quality scores under different land conditions-natural vs degraded-as well as an analysis of the consistency between Tier 1, which considers only the topsoil (0-20 cm), and Tier 2, which incorporates a complete profile based on multiple soil horizons.

Through this work, the thesis aims to contribute to the development of a standardized and replicable methodology for assessing soil quality in extractive environments. This approach is intended to support early decision-making in land rehabilitation processes and aligns with the broader goals of the EU Directive on Soil Monitoring and Resilience and the ROTATE project's sustainability objectives.

2 Materials and Methods

This chapter presents a general overview of the Soil Survey and Health Conservation Management Plan (SSHCMP), in which the Preliminary Soil Quality Assessment System is framed. It explains the main steps of soil management proposed in the guide, divided into three modules. Each module focuses on a different activities of the mining process and includes specific actions and recommendations for each one. In addition, this thesis proposes a model specifically developed to assess the quality of mining soils. This model is based on the evaluation of several soil descriptors as a basis for assessing seven basic soil functions. The purpose of this model is to provide a screening tool that rates the soil health status during any phase of the mining project.

2.1 General Overview of the SSHCMP

The Soil Survey and Health Conservation Management Plan (SSHCMP) is a comprehensive monitoring framework designed to provide a standardized methodology to ensure the proper health of mining soils through the monitoring of key indicators, as well as to propose actions to prevent or minimize the loss of the soil's original properties during the extraction, handling, storage, and backfilling phases.

Given that vegetation and land use are closely related, and that the integration of mining and quarrying operations into the ecological landscape largely depends on a stable vegetative cover, rehabilitation actions are usually focused on adapting land conditions to meet vegetation requirements. Thus, the restoration plan must incorporate various measures to control erosion, stabilize the terrain, and prevent or correct potential contamination issues, among other actions (López Jimeno, 2020). Currently, most rehabilitation work carried out on extractive industry sites begins with the re-placement of preserved or imported soil materials on denuded or waste-covered areas, following topographic reshaping. The main proposed measures focus on landform reshaping to prevent erosion risks, while revegetation techniques have limited application due to the slow progress of the process in the prevailing climatic conditions (Sigcha et al., 2018).

For ensuring the provision of a soil layer in the altered area, with suitable edaphic characteristics and sufficient thickness to allow vegetation to take root, the SSHCMP supports two essential aspects:

- The careful removal and handling of soil during the pre-extraction phases, as well as its storage and backfilling once extraction activities have begun.
- The characterization and monitoring of soil health based on a set of soil indicators, grouped according to soil functions.

To make sure that everything is done in the best way, the SSHCMP includes a set of methods and actions that need to be applied during the three main phases of any open-pit mining project (IHOBE, 2005). These phases are:

- (i) the preparatory phase, which involves studying the site and preparing the area for extraction, including building access roads and setting up drainage and sealing systems.
- (ii) the filling phase, which is when the extraction itself takes place, following the exploitation plan, and materials start to be moved or filled.
- (iii) the sealing and closure phase, when the restoration of the area begins and actions are taken to recover the landscape.

The SSHCMP is developed to protect soil quality during each of these phases by applying clear and standardized methods, along with preventive or corrective actions, depending on the needs of each phase.

In addition, the plan proposes a model specifically developed to assess the quality of mining soils, which is the main focus of this thesis (see Section 2.2). This model is based on the evaluation of several soil descriptors as a basis for assessing seven basic soil functions. The purpose of this model is to provide a screening tool that rates the soil health status during any of the three phases of the mining project.

The SSHCMP is structured around three main methodological modules (see Figure 5), which organize and structure its actions and tools. These are:

- Module I: Soil characterization and diagnosis, focused on the assessment of soil properties.

- Module II: Measures to protect and maintain soil quality, which defines interventions to prevent soil degradation.
- Module III: Rehabilitation and restoration of mining soils, focused on the functional and ecological recovery of soils following mining activity.

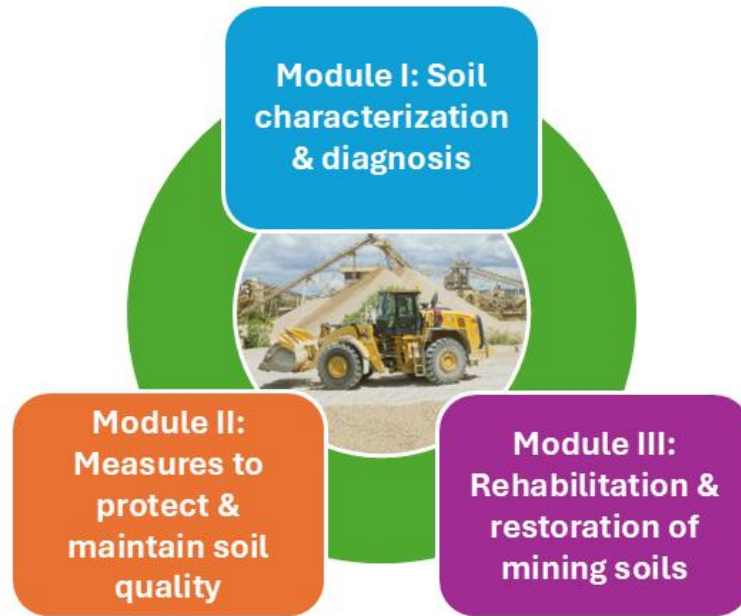


Figure 5 – SSHCMP structure

2.1.1 Module I: Soil characterization and diagnosis

Soil characterization is of particular importance within the SSHCMP framework, as the description of both natural and mining soils is carried out during this stage. The methodologies and actions described in Module I are aimed at four main objectives:

- The design of the sampling plan, including sampling and analysis techniques.
- The design of the soil condition assessment system.
- The establishment of baseline conditions regarding soil status.

The module also includes the selection of relevant physical, chemical, and biological indicators, as well as the definition of the soil quality evaluation system, which is described in detail in Section 2.2. The results obtained by applying real data to this system are presented and discussed in Chapter 3.

Background Information

The initial planning includes the analysis of historical records, geological and hydrographic maps, as well as land use studies. According to Directive on Soil Monitoring and Resilience (Art. 24a), Member States must base their assessments on the delineation of their respective soil districts and units. Soil type and land use are considered the two essential elements that should be used as a common basis to ensure adequate harmonization between countries.

Soil type can be determined using the map of Soil Regions of the European Union and Adjacent Countries (2005), which reflects the general conditions of soil development at the landscape scale. This map is based on the soil classification established by the World Reference Base for Soil Resources and relies on homogeneous and comparable continental-level data, including variables such as climate, topography, geology, relief, and vegetation. In this regard, it is advisable to consider local climatic and environmental conditions, use more precise or recent national or regional data when available, records provided by soil managers, and measurements made within the framework of regulations or initiatives (e.g., Land Use/Cover Area Frame Statistical Survey (LUCAS)).

Sampling design

Directive on Soil Monitoring and Resilience (Art. 31) recommends that the distribution of random sampling points be defined using geostatistical methods based on soil units. Additionally, Annex II of the Directive establishes minimum criteria for sampling design:

- Sampling scheme: The sampling plan should be based on a stratified random design according to the defined soil units.
- Statistical representativeness: The number and location of sampling points should reflect the variability of the selected soil descriptors, ensuring a maximum coefficient of variation of 5%.
- Determination of sample size and distribution: These should be calculated using appropriate statistical procedures, such as the Bethel algorithm (Bethel, 1989).
- Location of sampling points: Samples should be taken at predetermined locations unless circumstances prevent this (e.g., water-saturated soil or excessive presence of rocky material).

- **Composite samples:** When taking composite samples, they should be prepared from at least 5 subsamples mixed thoroughly to obtain a homogeneous sample (for volatile organic contaminants, composite samples are discouraged, and grab samples should be used instead).
- **Surface preparation before sampling:** In non-forested areas, organic residues and debris must be removed from the soil surface, while in forested areas, the surface horizon should be sampled separately, recording its thickness and weight.
- **Sampling depth:** Samples must be taken to a minimum depth of 30 cm, recording soil type and horizons.
- **Undisturbed samples:** To determine certain parameters, such as bulk density or saturated hydraulic conductivity, undisturbed samples must be collected (if the sampling point has a high coarse fragment content, it may be excluded from bulk density analysis).

Establishment of soil baseline

The establishment of the soil baseline condition constitutes a critical stage in the pre-operational process, as it provides the edaphic reference foundation for effective future rehabilitation. Since extractive industry activities involve the alteration or destruction of the original soil, it is essential to have a detailed technical characterization of the soil before any intervention. This characterization guides corrective and restorative measures according to the original site conditions (Arranz-González, 2004b) and helps avoid common mistakes in later phases, such as lack of suitable topsoil or ineffective revegetation efforts. The main objective of sampling during this phase is to accurately describe the edaphic properties of the original terrain, establishing an operational baseline for future soil health assessment and restoration strategy design.

In addition to sampling, soil characterization at baseline must include a description of soil profiles through test pits and/or boreholes.

- **Test pits:** A minimum depth of 1 meter is recommended, with at least one test pit per hectare of affected surface. Test pits may be specifically dug or use existing geotechnical excavations, provided they meet the defined technical criteria.
- **Boreholes:** Manual augers or probes may be used to obtain samples at depths equivalent to test pits, especially in difficult-to-access terrain. Additionally,

boreholes can be extended to greater depths when deeper soil characterization is required for specific analyses.

In any case, samples must be fresh and not exposed to the elements for prolonged periods. Old cuts (e.g., slopes or road margins) may be used exceptionally for qualitative *in situ* observations.

All information obtained during the soil profile description must be systematically recorded in a datasheet. It is recommended to use a format that includes fields such as soil classification, profile location, depth, slope, description of the soil and other relevant data.

2.1.2 Module II: Measures to protect and maintain soil quality

This Module refers to the methodologies and preventive actions that must be carried out during the preparatory and operational phases of an open-pit mining project. Site characterization is of special relevance within the framework of the SSHCMP, as the description of the natural soil properties is conducted during this stage.

The methodologies and actions applied during this phase focus on two main objectives:

- Preventive practices aimed at soil management and storage.
- Preventive practices aimed at maintaining soil quality.

Soil management and storage

Proper topsoil management is crucial for the ecological restoration of mining and quarrying sites, particularly for successful revegetation and the preservation of soil properties. From the early stages of the project, soil quality must be protected to support plant growth and ecosystem stability. This involves careful removal and handling of the soil during pre-extraction, and its proper reapplication during restoration, ensuring suitable thickness and conditions for plant development (Martínez-Ruiz et al., 2021a). To maintain its fertility and structure, the soil should be extracted in a controlled way and stored under conditions that prevent degradation. Key operations include:

A) Selective removal of topsoil, preserving different soil horizons for later reconstruction;

Soil removal should be done progressively, prior to extraction in each affected area, and always following best soil management practices to preserve its functional properties.

Key actions at this stage include:

- Identification of soil horizons, based on field observations (test pits, boreholes, visual analysis) to guide proper extraction;
- Removal of vegetation cover to avoid anaerobic conditions and degradation of stored soil;
- Seed collection of native plant species to support ecologically integrated revegetation;
- Separate extraction of soil horizons, avoiding mixing to preserve fertility and biological activity;
- Prevention of soil deterioration during handling, minimizing compaction, contamination, and structural loss through suitable equipment and conservation techniques.

B) Proper storage and conservation, avoiding compaction, erosion, structural loss and contamination.

Ideally, soil should be removed and immediately spread in restoration areas to avoid temporary storage. When this is not possible, soils must be stored in conditions that preserve their quality. Recommended stockpile characteristics vary by soil type, with limits on height and storage duration to prevent degradation.

Key best practices for temporary soil stockpiling include:

- Low-height stockpiles (≤ 3 m), spread in thin, uniform layers (≥ 30 cm) to prevent compaction and allow aeration;
- Separate storage of soil horizons to avoid cross-contamination and preserve fertility;
- Strategic placement in sheltered areas, away from trees, water bodies, and active mining zones, ideally forming perimeter windbreaks;
- No machinery traffic on stockpiles, to avoid irreversible compaction;
- Stabilization for long-term storage (> 6 months) through temporary vegetation (preferably legumes) and mulching.

Maintaining soil quality

Preserving soil quality throughout mining and quarrying operations is essential for sustainable land management and successful ecological restoration. The topsoil, rich in physical, chemical, and biological properties, plays a vital role in supporting plant growth, water regulation, and microbial activity. However, extraction activities can severely degrade soil structure and function. Therefore, a set of preventive practices must be applied before, during, and after operations to mitigate risks such as compaction, erosion, contamination, and invasive species introduction.

A) Pollution Prevention

Soil pollution must be prevented to maintain its ecological integrity and ensure its reuse in restoration. Pollution sources include industrial waste, fuel and chemical spills, and improper waste handling. Preventive strategies include:

- Baseline soil studies and continuous monitoring, with regular analyses of physical, chemical, and biological parameters
- Designated zones for hazardous substances, with impermeable surfaces, retention systems, and proper drainage, located away from water bodies and soil stockpiles.
- Strict waste management protocols, including segregation, pretreatment, and disposal in authorized facilities. Hazardous waste must be classified and treated accordingly.
- Soil assessments before reuse, especially for restoration purposes. Contaminated materials should be remediated or replaced using low-impact methods.

B) Selection of Off-Site Soil Inputs

When on-site soil is insufficient or degraded, external soils can be used to restore topography and soil functions. Sources include overburden, washing sludge, and rejected plant materials from the same site, which may need enhancement with organic matter or plant residues (López Jimeno, 2020). For soils from other locations, prior characterization is necessary to ensure compatibility in terms of texture, structure, infiltration, and water retention.

A promising alternative is the use of technosols: engineered soils made from compost, manure, construction waste, and sewage sludge. These materials improve fertility, structure, and water retention, and help control acid mine drainage. Before application, all soils must be checked for the presence of invasive species, and post-application monitoring must be implemented to ensure performance. Technosols, in particular, require detailed modeling and monitoring to optimize long-term outcomes.

C) Compaction Prevention

Soil compaction reduces porosity and disrupts aeration, infiltration, and root penetration. It depends on factors such as texture, moisture, and machinery use (The Institute of Quarrying, 2025). Wet soils are more vulnerable to compaction, especially clay-rich or organic soils.

Machinery type and handling practices significantly affect compaction levels: lighter machinery exerts less pressure but may increase soil traffic. Therefore, appropriate equipment and techniques must be selected carefully.

Before topsoil application, areas affected by buildings or machinery must undergo decompaction using scarification (to ~20 cm), subsoiling (to ~60 cm), or deep ripping (to ~1 m), depending on prior disturbance. These actions must follow contour lines to reduce runoff

D) Prevention of Invasive Species Introduction

Preventing the introduction and spread of invasive alien species (IAS) is critical for ecosystem recovery. IAS can alter ecological balance, reduce biodiversity, and cause environmental and economic harm.

Preventive measures include selecting appropriate soil and seeds, consistent with the native environment and early detection and rapid response programs for monitoring and control

Once IAS are detected, control methods include (López Jimeno, 2020):

- Chemical control: Using approved herbicides like glyphosate, with caution to avoid runoff, non-target species impact, or application during rain or wind.

- Physical control: Manual or mechanical removal of plants, especially effective at early stages. Soil should be moist to allow complete root extraction. Mulching can also help suppress regrowth and prevent erosion.
- Biological control: Introducing natural enemies of the IAS. While effective, this carries ecological risks and must be carefully studied before implementation.

All removed invasive material must be handled to prevent re-spread. Restoration efforts should prioritize reintroducing native species with functional traits that limit IAS establishment. Enhancing functional diversity also helps close ecological gaps that invaders might exploit.

2.1.3 Module III: Rehabilitation and restoration of mining soils

Rehabilitation of mining-affected soils is essential to restore ecosystem functions and ensure sustainable land use. This module outlines key restoration actions, aligned with the diagnosis in Module I and management strategies from Module II. These include using soil amendments, erosion control measures before vegetation cover develops, and restoring structure through scarification. When topsoil is lacking, suitable alternative materials must be used (Gegúndez, 2022).

Mine closure planning

Mine closure involves several stages: planning (detailed activity design), execution (e.g., reforestation, demolition), and long-term monitoring to avoid future impacts (Cooke & Johnson, 2002). Closure should be considered from the start of a mining project, with attention to site geology and edaphic properties to guide physical, chemical, and biological restoration. Soil tests (pH, metals, nutrients) help identify critical areas. Clear, metric-based criteria support decision-making. Restoration includes revegetation and amendment use to recover ecological conditions (López-Marcos, 2020). Long-term or permanent actions may be needed (e.g., water treatment), alongside temporary monitoring strategies (Balaguer et al., 2014).

Backfilling of excavations and disposal of wastes

Terrain reshaping aims to restore safe, functional topography suitable for future land use. Key actions include morphological adaptation, slope design, and berm construction. Morphological adaptation involves earthworks like excavation, filling, and terracing to create gentle slopes that blend with the environment and support natural drainage. Existing site features can be reused—for example, flooded gravel pits can become wildlife habitats or recreational areas.

Slopes should be designed for geotechnical safety and landscape integration, ideally with gradients gentler than 3H:2V to promote stability and revegetation. Irregular, rounded profiles are preferred over flat or sharp edges to blend terrain naturally. Unstable slopes require study and may need drainage or structural correction, especially in visible areas. Berms or terraces reduce slope steepness and visual impact, but regular terracing is discouraged unless needed for stability. Erosion control measures, such as reshaping and drainage treatments, are essential before revegetation, adapted to substrate hardness and slope.

Corrective actions

Despite planning and sustainable management, significant soil damage often needs corrective measures after mining ends. These focus on restoring soil function by stabilizing physical, chemical, and biological properties to improve structure, moisture retention, fertility, and erosion resistance. Corrective actions cover contaminated soil treatment, acid drainage control, drainage improvement, use of amendments, organic matter addition, native reforestation, and habitat creation. Each requires precise diagnosis and appropriate technology selection based on site conditions. These actions are briefly described in this section, as their developed structure is presented in the methodological guide.

A) Drainage improvement

Slope stability in mining areas relies heavily on proper drainage. Excess water weakens soil, increasing landslide and erosion risks, especially when soil is compacted by heavy machinery. Drainage methods include porous pipes, berms, and ditches to remove surface and subsurface water. For mining soils, mechanical tillage breaks compaction, while

adding organic matter or sand improves structure. Deep-rooted plants help water infiltration and strengthen the soil, reducing erosion and restoring natural water flow.

B) Use of amendments

Soil amendments improve degraded soils by enhancing water retention, fertility, and microbial activity. Common amendments like compost, biochar, lime, and gypsum adjust pH, immobilize contaminants, and improve soil texture. The EU promotes the reuse of mining residues for sustainable restoration and waste reduction. Studies show organic amendments boost microbial biomass and plant growth. Effective restoration requires careful diagnosis, lab and field testing, and monitoring to ensure environmental safety and soil function recovery

C) Supply of fertile soil and organic matter

Recovering topsoil is key for vegetation restoration in mining areas. It must be carefully removed, stored, and reapplied to avoid erosion and compaction. Projects estimate the topsoil needed for slopes and embankments, prioritizing critical zones if limited. Machinery with low compaction impact is used, and scarification before and after spreading helps roots penetrate and water move. This supports plant establishment and long-term ecosystem recovery.

D) Treatment of contaminated soil

Soil remediation depends on contaminant type and site conditions. Organic pollutants are treated with bioremediation, chemical oxidation, or thermal methods; heavy metals with immobilization or extraction techniques. Mining sites often need combined solutions, but steep terrain and compacted soils limit access and effectiveness. Integrating soil and groundwater treatments is crucial. Success hinges on adapting methods to local geology and contaminants, often using innovative hybrid approaches tested in Europe.

E) Control of acid drainage or toxic leachates

Acid drainage from sulfide weathering in mines acidifies water and soil, harming ecosystems and contaminating water sources. It originates from mine openings or waste piles and carries heavy metals. Measuring flow and pollutant loads helps assess impact. Passive solutions like technosols—engineered soils made from local materials and

bioactive compounds—neutralize acidity and improve fertility. Projects in Spain have shown these methods effectively control acid drainage and aid environmental recovery.

F) Reforestation with native species

Restoring vegetation with native plants helps recover ecological balance and prevents invasive species from reducing biodiversity. Species selection considers climate, soil, land use, and landscape aesthetics. Using local plants ensures better integration and less maintenance. This approach controls erosion, blends with surroundings, and rebuilds habitats, supporting long-term ecosystem health.

G) Creation of habitats for local fauna

Mining disrupts habitats essential for wildlife, which need food, shelter, water, and space. Restoration creates or improves these areas by planting native vegetation and establishing “biodiversity islands” that support insects, birds, and mammals. Promoting diverse and connected habitats like meadows, wetlands, and forests allows species migration and plant dispersal. Careful land planning supports sustainable biodiversity recovery after mining.

2.2 Soil Quality Evaluation System

This thesis has been carried out within the framework of the EU-funded ROTATE project, with a particular focus on Module I of the Soil Survey and Health Conservation Management Plan (SSHCMP). This module addresses the characterization and evaluation of soils to be removed and stored from the future mining area. As detailed in Section 2.1.1, it centres on the diagnosis of soils affected by mining and quarrying activities. A key outcome of Module is the development of a soil quality evaluation system, which is the core foundation of this thesis.

The proposed system was adapted from Destisol, a model originally developed for the evaluation of urban soils (Séré et al., 2024). Within the framework of the SSHCMP the model was restructured and expanded to better reflect the specific conditions and needs of mining and quarrying environments. This adaptation involved the selection of relevant

soil functions, such as organic matter recycling, erosion control, and carbon storage, that are crucial for the health and quality of the soil.

The development of this system is aligned with the recent EU Directive on Soil Monitoring and Resilience (COM, 2023), which emphasizes the need to ensure the quality and comparability of soil measurements across Europe. According to the directive, when reference methodologies are available, they should be used; otherwise, equivalent methods may be applied, provided they are documented in scientific literature or publicly accessible and supported by validated transfer functions. Particular relevance is given to the use of CEN (European Committee for Standardization) methodologies, which should be preferred when available. These harmonized technical standards are recognized at the European level and are fundamental to ensuring consistency, transparency and scientific robustness in soil evaluation processes. In this context, the adaptation of an existing model such as Destisol, which is documented in the literature and based on a functional approach, can be considered a valid methodological choice.

The structure of the model follows a tiered approach (Tier 1 and Tier 2), allowing it to be applied flexibly depending on the available data and technical capacity.

- **Tier 1** serves as the core and recommended methodology, focusing on the evaluation of the topsoil layer (0–20 cm) as a single diagnostic unit.
- **Tier 2** is an optional advanced method, which builds upon Tier 1 by performing a horizon-based analysis (A, B, C) that incorporates depth and functional relevance into the final scores. At the end of the process, it provides an overall rating that integrates the results from all evaluated soil horizons.

It is based on a set of selected physical, chemical, and biological indicators, which are translated into numeric scores from 0 to 3, reflecting their contribution to different soil functions. These scores are then used to evaluate the soil's functional health and its potential to support successful land rehabilitation.

The model's architecture is based on the evaluation of 11 physico-chemical soil descriptors, which are used to rate 7 basic soil functions through a detailed set of decision rules. The algorithm, described in Section 2.2.2 employs a multi-criteria approach to process the values of the physical, chemical, and biological descriptors and assign scores

to each evaluated function. At the end of the process, it provides an overall rating that integrates the results of all the 7 soil functions. The algorithm not only considers the value ranges of each descriptor but, in some cases, the value of certain key descriptors can automatically determine the score of a function regardless of other parameters. Additionally, some descriptors, such as soil depth or pH, have specific reference values depending on the function being evaluated, allowing the model to be flexible and adapted to each context.

The following subsections describe the structure of the model in detail, including the selection of soil descriptors (Section 2.2.1), the logic used to assign function scores (Section 2.2.2), and the algorithmic workflow that translates input data into final outputs (Section 2.2.3). The testing of the system using real datasets is presented in Chapter 2.3.

2.2.1 Soil descriptors selection

A soil descriptor is understood as a parameter that describes a physical, chemical, or biological characteristic of soil health. This concept is considered synonymous with “soil indicator,” a term widely used in the scientific literature, which usually refers to the link between a soil property and a reference framework with the purpose of assessing soil functionality (Doran & Parkin, 1997). The reference framework for the selection of the indicators and the creation of the model is the Directive on Soil Monitoring and Resilience.

A total of 11 descriptors have been selected based on their applicability to the open-pit mining context and in accordance with the objectives set out in the methodological guide. It is important to note that some descriptors refer to the entire soil profile (Soil Depth and Soil Texture), while others are specific to individual soil horizons if we refer to Tier 2. The complete list of descriptors used and the reference methods for their determination can be found in Table 10.

Table 10 – Soil descriptors and their reference methods

Descriptor	Units	Method
Soil Depth	cm	Direct measurement
Soil Texture*	%	ISO 11277: Determination of the particle size distribution of mineral matter in soils
pH	-	ISO 10390: Determination of pH in H ₂ O, KCl and CaCl ₂ extract
Organic Matter (OM)	SOC/clay ratio	ISO 10694: Determination of organic carbon and total carbon after dry combustion
Erosion Rate	t ha ⁻¹ y ⁻¹	RUSLE2015: 100 m resolution pan-European soil erosion model estimating water-induced soil loss using updated environmental data
Bulk Density	g cm ⁻³	ISO 11272: Determination of bulk dry density
Nitrogen (N)	g kg ⁻¹	ISO 11261: Determination of total nitrogen in soil by a modified Kjeldahl method
Phosphorous (P)	g kg ⁻¹	ISO 11263: Spectrometric determination of soluble phosphorus in a solution of sodium bicarbonate (P-Olsen)
Saturated Hydraulic Conductivity	cm d ⁻¹	ISO 17313: Determination of the hydraulic conductivity of saturated porous materials
Retention Capacity	% water / total soil	ISO 11274:2019: Laboratory methods to determine soil water-retention characteristic
Trace Elements Concentration	mg kg ⁻¹	ISO 54321: <i>aqua regia</i>

Soil function refers to the fundamental roles that soil plays within ecosystems, independently of human interests (Seybold et al., 2018). These functions operate through complex interactions with the biotic and abiotic components of the soil's physical and chemical environment. As noted in the previous section, soil descriptors are essential for assessing these functions, as they allow the measurement of soil performance based on various properties. These descriptors are particularly useful in urban, industrial, and mining contexts, where soil quality may be altered by human activities.

Although soil performs many functions, this assessment system focuses on seven key soil functions, grouped into five main categories, as proposed by Séré et al. (2024). This approach allows for a structured analysis of how soil fulfils its essential roles in ecosystems. Additionally, it helps identify critical functions and facilitates decision-making for the conservation and improvement of mining soils.

The five categories, along with the functions they include, are detailed below:

- **Internal soil functioning**

This category covers two key functions: organic matter recycling, which ensures the renewal of resources necessary for life in the soil, and erosion control, which protects the soil against the loss of the topsoil layer. The two functions with their respective descriptors are listed in Table 11 and Table 12.

Table 11 – Descriptors considered in the Organic recycling function

Organic Recycling Function	
Descriptor	Units
Soil Depth	cm
pH	-
OM	SOC/clay ratio

Table 12 – Descriptors considered in the Erosion function

Erosion Function	
Descriptor	Units
Erosion rate	t ha ⁻¹ y ⁻¹

- **Carbon storage**

This function focuses both on the current stock of carbon stored in the soil and on the additional carbon capture, assessing the soil's potential to contribute to climate change mitigation. The descriptors considered for this function are detailed in Table 13.

Table 13 – Descriptors considered in the Carbon function

Carbon Function	
Descriptor	Units
Soil Depth	cm
OM	SOC/clay ratio

- **Soil fertility**

This function emphasizes physico-chemical considerations, particularly regarding herbaceous vegetation and rooting depths, aspects that reflect the soil's capacity to support plant life. The descriptors considered for this function are detailed in Table 14.

Table 14 – Descriptors considered in the Fertility function

Fertility Function	
Descriptor	Units
Soil Depth	cm
pH	-
N	g kg ⁻¹
P	g kg ⁻¹
Compacity (Sandy)	g cm ⁻³
Compacity (Loamy sands / Sandy loams)	g cm ⁻³
Compacity (Silts and silty clay loams)	g cm ⁻³
Compacity [Medium clays (35–45% clay)]	g cm ⁻³
Compacity [Pure clays (>45% clay)]	g cm ⁻³

- **Water circulation**

This category evaluates two fundamental aspects of water in the soil: water retention and water flow, both of which are crucial for water availability in the ecosystem and water regulation. The descriptors considered for each of these functions are detailed respectively in Table 15 and Table 16.

Table 15 – Descriptors considered in the Water retention function

Water Retention Function	
Descriptor	Units
Soil Depth	cm
Retention capacity	% water / total soil

Table 16 – Descriptors considered in the Water infiltration function

Water Infiltration Function	
Descriptor	Units
Soil Depth	cm
Saturated Hydraulic Conductivity	cm d ⁻¹

- **Soil contamination**

This final category is dedicated to assessing the presence and impact of contaminants in the soil, considering soil quality throughout its entire profile. The descriptors considered for this function are detailed in Table 17.

Table 17 – Descriptors considered in the Contamination response function

Contamination Response Function	
Descriptor	Units
Soil Depth	cm
Trace Elements Concentration	mg kg ⁻¹
pH	-

Each descriptor used in the model is assigned a score from 0 to 3, based on the value it takes within the soil profile. These scores reflect how suitable each descriptor is for supporting a specific soil function. The exact value ranges that correspond to each score level are detailed for all descriptors and functions in Annex A. In addition to the scoring ranges, Annex A also shows which descriptors are considered key factors. These are the most important indicators for a given function. If the score of a key factor is 0, then the entire function score is automatically set to 0, even if the other descriptors have higher values. This rule ensures that a critical deficiency in a single parameter is not compensated by the performance of others.

2.2.2 Soil function scoring

As explained in Section 2.2.1, each descriptor contributes to the assessment of at least one soil function. In the model proposed by Destisol, each descriptor is scored according to the value ranges defined for the specific function it supports. This means that a single descriptor, such as pH or soil depth, may receive different scores depending on the function being assessed, as the value ranges and thresholds vary across functions.

The Tier 1 model scores each function on a scale from 0 to 3, based on the descriptor values of the top soil. No weighting by horizon or adjustments for depth distribution are applied, meaning the scoring relies solely on the properties observed in the surface layer without considering variations deeper in the soil profile.

$$T1_f = \frac{1}{n} \sum_{d=1}^n D_d$$

Where,

D_d value of descriptor d in the topsoil,

n number of descriptors evaluated.

In the case of the Tier 2, each function receives a score ranging from 0 to 3 for each evaluated horizon, based on the weighted average of the scores of the descriptors involved. To simplify the evaluation model and make the analysis more accessible, only the three basic horizons of a generic soil have been considered, namely horizons A, B, and C (see Section 1.1.1). Each of these horizons performs specific functions within the soil ecosystem, and their capacity to carry out key functions such as fertility, erosion control, water retention, and organic recycling varies according to their physical, chemical, and biological characteristics. In other words, not all horizons carry the same weight within the overall soil.

For this reason, the Tier 2 model calculates a global weighted score for each soil function (i.e., considering the full set of horizons that make up the evaluated soil) by assigning weights to the horizons according to their thickness and functional relevance, aiming to increase the accuracy and ecological representativeness of the model. For each soil function f , the global score is obtained as:

$$T2_f = \frac{\sum_i (S_{i,f} \cdot E_i \cdot R_{i,f})}{\sum_i (E_i \cdot R_{i,f})}$$

Where,

$S_{i,f}$ is the score of function f in horizon i ,

E_i is the thickness of horizon i (in cm),

$R_{i,f}$ is the functional relevance of horizon i for function f (a value between 0 and 1).

Below are the functional relevance factor scores ($R_{i,f}$) assigned to the three basic horizons, along with their justifications (Table 18):

1. **Horizon A:** Due to its high concentration of organic matter and its role in supporting root growth, this horizon receives the highest scores for functions such as fertility (1.0), organic recycling (1.0), and erosion control (1.0), as it is more susceptible to loss through erosion processes. Its water retention capacity (0.8) is good, although not as high as in deeper horizons, due to its variable structure and texture.
2. **Horizon B:** Since this horizon is crucial for accumulating nutrients leached from horizon A, its role in water storage (1.0) and infiltration (1.0) is important because of its higher density and porosity, which facilitate water retention and movement. Although it plays a significant role in contamination (1.0), its fertility (0.5) is moderate due to its lower content of available nutrients compared to horizon A.
3. **Horizon C:** This horizon has less interaction with biological processes and a limited capacity to store nutrients or organic matter. However, it plays a fundamental role in water retention (0.6) and carbon storage (0.8). Its low organic matter content makes it less capable in fertility (0.2) and organic recycling (0.2). Its role in water infiltration (1.0) is high, especially in soils with porous materials, such as sandy soils or fractured rock.

However, it is important to note that these factors are proposed as guidelines and can be replaced or adjusted by the facility manager or informed by expert judgment, allowing for greater flexibility based on specific circumstances or local knowledge.

Table 18 – Factors of functional relevance of horizons A, B and C for the function

Function	Horizon A	Horizon B	Horizon C
Recycling	1.0	0.6	0.2
Erosion	1.0	-	-
Carbon Storage	0.6	1.0	0.8
Fertility	1.0	0.5	0.2
Water Infiltration	0.7	1.0	1.0
Water Retention	0.8	1.0	0.6
Contamination	0.6	1.0	1.0

In both the Tier 1 and Tier 2 approaches, the overall score obtained for each soil function is ultimately represented on a scale from 0 to 3, with intervals of 0.75. This scale allows the classification of soil function quality into four distinct levels (Figure 6), which are as follows:

High [2.25–3] – Optimal: This level reflects healthy functions with optimal performance. Soils with functions in this category can be considered "optimal" or of "high quality," with ideal conditions to sustain healthy ecosystems and provide essential ecosystem services.

Moderate [1.5–2.25] – Acceptable: Functions with scores in this range show acceptable, though not optimal, quality. They perform reasonably in terms of the evaluated function but could still benefit from management practices to reach their full potential. These are considered functional soils but with room for improvement.

Low [0.75–1.5] – Deficient: Functions within this range have deficient quality, meaning their performance is suboptimal. This state suggests that soils require intervention to restore the compromised functional capacity or capacities.

Very Low [0–0.75] – Critically degraded: This level indicates severely deteriorated or highly compromised functionality. Soils with functions in this category show extremely degraded conditions, requiring urgent intervention to restore the compromised functional capacity or capacities.

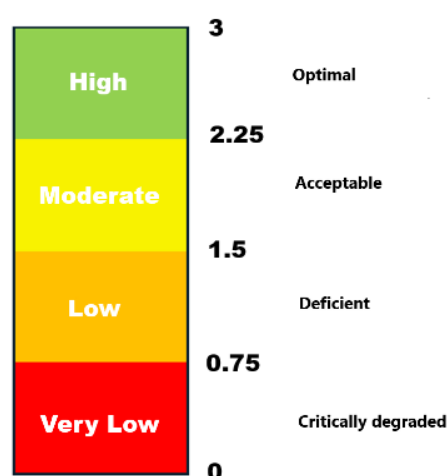


Figure 6 – Soil quality scale for the assessment of the level of functional quality of soils

2.2.3 Algorithm description and flowchart

To support the application of the scoring model and provide a visual overview of the process, a general flowchart has been developed (Figure 7). This diagram illustrates the logical sequence followed by the Excel-based tool, from data input to the final evaluation of soil quality. It serves as a reference for understanding the structure of the algorithm and its iterative application across all soil functions.

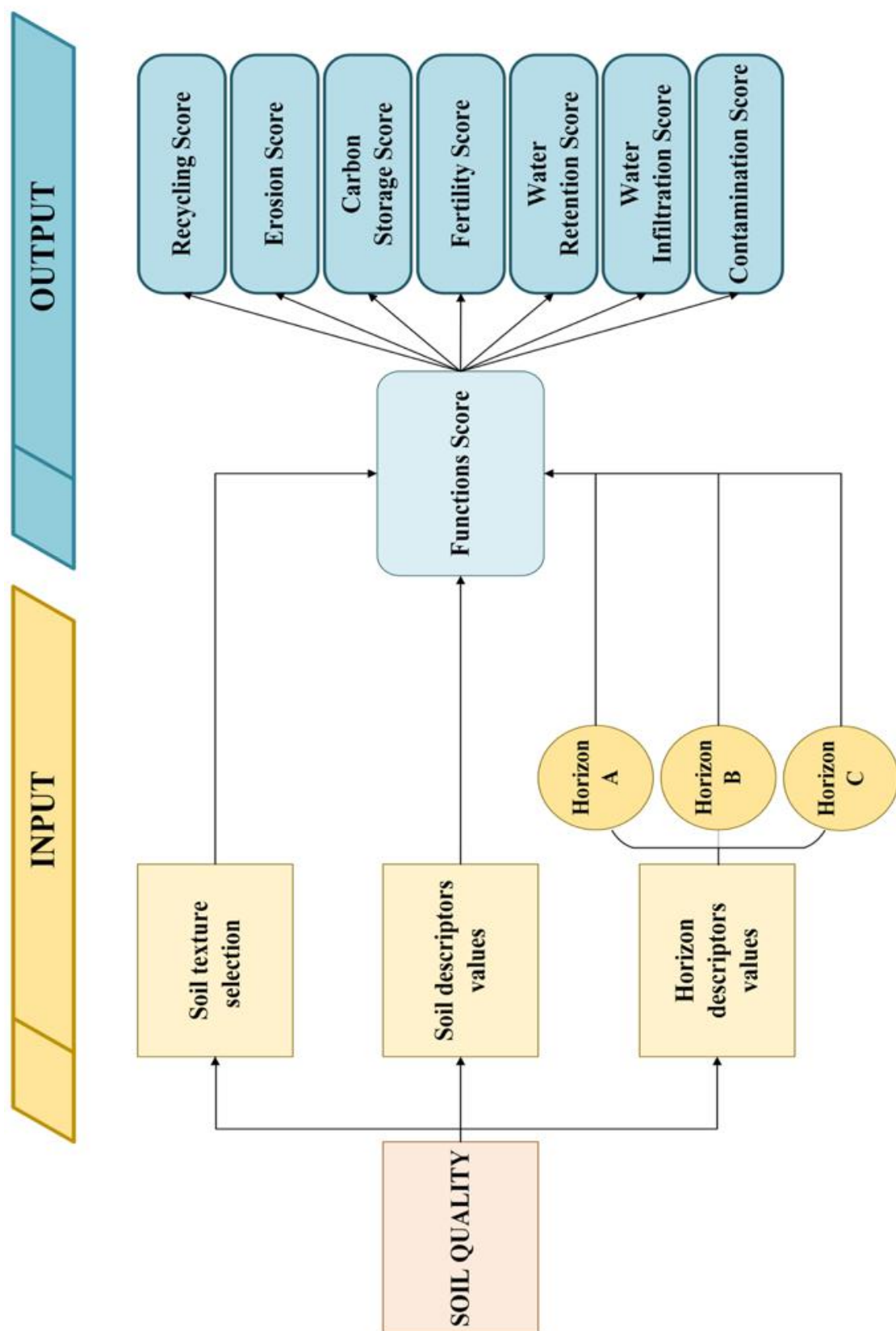


Figure 7 – General flowchart for assessing overall soil quality in terms of the seven basic functions. In the case of Tier 1, the values for the A, B, and C horizons must be replaced with a single representative value per descriptor for the topsoil

In addition to the general diagram, individual flowcharts for each of the seven soil functions are provided in Annex B, offering a more detailed view of how the scoring rules are applied for each specific function.

The soil quality assessment algorithm was developed in Microsoft Excel and is structured across three main windows: one for data input and two for output display, at the horizon and soil levels respectively. The purpose of the algorithm is to translate physical and chemical soil descriptors into functional scores, representing the performance of each soil function, in line with the approach proposed by Séré et al. (2024). The process is applied iteratively for each of the seven selected soil functions and follows six main steps:

1) Selection of Soil Texture and Horizon

The first step involves selecting the textural class of the soil under evaluation. This is done in the first Excel window titled “Soil descriptors”, where the user chooses among five textural classes: Sandy, Loamy sands / Sandy loams, Silts and silty clay loams, Medium clays (35–45% clay), Pure clays (>45% clay). Texture plays a crucial role as it affects other descriptors such as bulk density and water retention. Additionally, if Tier 2 is applied, the user specifies the depth and name of the horizon being assessed (A, B, or C), enabling horizon-level evaluation.

2) Data Acquisition of Soil Descriptors

In the same input window, the user must provide values for 11 soil descriptors, some of which are assessed at the whole-profile level (e.g., soil depth), while others, if Tier 2 is applied, are evaluated per horizon (e.g., pH, organic matter, nitrogen, phosphorus, , and the concentration of the most at-risk trace element). The Soil Screening Level (SSL) for the most concerning contaminant on the site must also be entered to support the evaluation of contamination.

3) Assignment of Scores to Descriptors

Each descriptor is associated with a defined value range, which corresponds to a score from 0 to 3. These ranges are established based on standard laboratory methods and thresholds defined in the methodological guide (see Table 11). It is important to note that some descriptors have different thresholds depending on the specific function being

assessed. For example, pH or soil depth may contribute differently depending on whether the function relates to plant productivity or contaminant retention.

4) Calculation of Function Scores at Horizon Level (only if Tier 2 is applied)

The algorithm then calculates the performance of each soil function within the selected horizon. The results of this step are displayed in the second window of the Excel tool titled “Horizons’ Scoring”, which presents the function scores for each of the three horizons (A, B, and C). Additionally, column charts provide a visual summary of the functional performance across the horizons, helping the user quickly identify which horizons are most vulnerable and which functions may require improvement.

5) Global Evaluation of Function at Soil Level

To obtain a comprehensive view of each function, the scores from all evaluated horizons (if Tier 2 is applied) are aggregated into a global soil function score, using a weighted average that accounts for the depth and importance of each horizon. If Tier 1 is applied a simple average of the soil descriptor’s score is computed. This final score is categorized into four quality levels: Very Low, Low, Moderate, High. The global evaluation is shown in the last window of the Excel tool, providing a clear summary of the overall soil quality status across all functions.

6) Iteration Across All Soil Functions

The full process is repeated independently for each of the seven soil functions. This modular evaluation allows for a detailed diagnosis of the soil's performance across various roles, including physical structure, nutrient retention, biological activity, and contaminant regulation, offering essential insights for land management and restoration strategies in open-pit mining contexts.

2.3 Testing of the model

The model described in Section 2.2 was tested using real soil data to evaluate its ability to assess soil quality under different environmental conditions and land degradation

scenarios. The testing phase was structured in two parts, each designed to verify specific aspects of the model's performance and applicability.

2.3.1 Comparison of Natural and Degraded Soils (Tier 1)

In the first part of the testing phase, the model was applied using the Tier 1 methodology, which evaluates only the topsoil layer (0–20 cm). This approach was selected both to align with the EU Directive on Soil Monitoring and Resilience, which promotes the use of harmonized datasets such as LUCAS and because the available degraded soil data refer exclusively to the topsoil. Using Tier 1 for both natural and degraded soils ensures that the results are methodologically consistent, reliable, and comparable. This allowed for the comparison between two contrasting categories of soil:

- Natural soils, selected from the LUCAS Topsoil 2018 dataset. Nine soil profiles were chosen to represent a diversity of land uses (three agricultural, three forest, and three semi-natural) and climatic conditions across different European countries. Selection criteria also included the completeness of key descriptors required by the model. Table 19 shows the location and the landuse of each soil, while Figure 8 shows their exact position on a map.

Table 19 – Location and land use of evaluated natural soils

Soil ID	Country	LONG	LAT	Landuse
N1	Portugal	-7,5322	37,7694	Forestry
N2	Portugal	-7,8197	37,7152	Forestry
N3	Finland	22,2336	60,9601	Forestry
N4	France	-3,6679	48,0424	Natural land
N5	Ukraine	23,2099	50,7237	Natural land
N6	Latvia	22,7911	56,8206	Natural land
N7	Poland	22,8138	51,9890	Agriculture
N8	Serbia	22,8733	43,7822	Agriculture
N9	Bulgaria	26,5452	42,8089	Agriculture



Figure 8 – Location of the 9 natural soil samples (Source: Google Earth)

- Degraded soils originated from an abandoned and highly contaminated mining site in northern Spain. A total of nine samples were selected from the available 27, with three profiles each representing the mining zone, the processing plant area, and the seasonal creek adjacent to the site. Within each zone, samples were chosen to reflect variability in contaminant concentration, pH, and organic matter content, ensuring a representative dataset for testing. Table 20 summarises the information about the location and the land use of the examined soils.

Table 20 – Location and land use of evaluated degraded soil

Soil ID	Country	LONG	LAT	Landuse
D1	Spain	-4,49947	42,94064	Mining area
D2	Spain	-4,49923	42,94047	Mining area
D3	Spain	-4,49892	42,94026	Mining area
D4	Spain	-4,49704	42,93899	Seasonal creek
D5	Spain	-4,49525	42,93846	Seasonal creek
D6	Spain	-4,49429	42,93824	Seasonal creek
D7	Spain	-4,49182	42,94212	Processing plant
D8	Spain	-4,49155	42,94215	Processing plant
D9	Spain	-4,49162	42,94234	Processing plant

Figure 9 shows the exact position of the abandoned mining site on a map, represented by a red circle, while Figure 10 shows a close up on the three areas of study (the mining area, the creek zone and the processing plant zone) and the location of the examined soil samples.



Figure 9 - Location of the abandoned mining site of the study (Source: Google Earth)

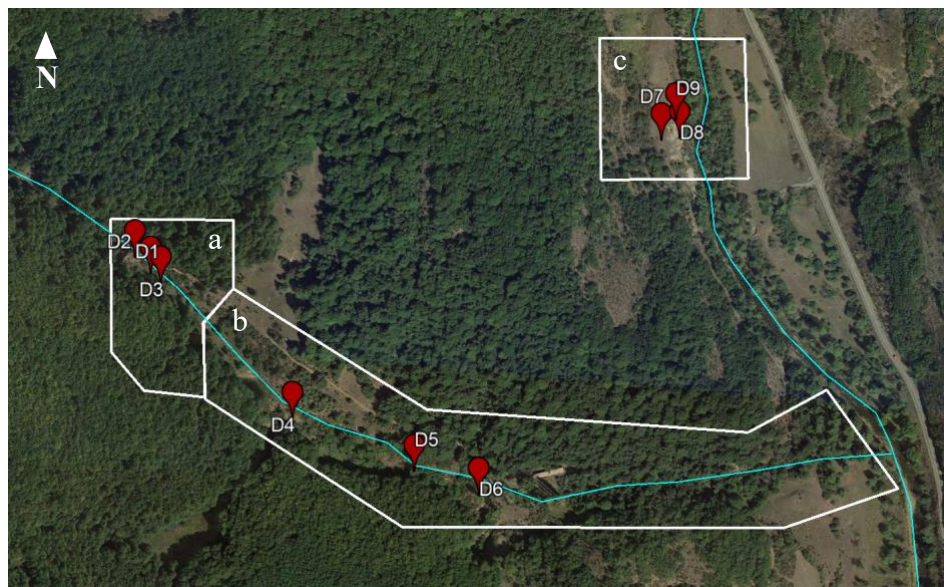


Figure 10 – Close up on the three zones of the degraded area: the mining area (a), the creek zone (b) and the processing plant zone (c) (Source: Google Earth)

Both sources of natural and degraded soil data are presented in Section 2.4, while the procedures used to prepare them for model computation are explained in Section 2.4.1.

The main goal of this comparative analysis was to assess the model's capacity to distinguish between soils in good ecological condition and those affected by severe

degradation and contamination, based solely on the topsoil indicators defined in the Tier 1 structure.

2.3.1 Comparison of Tier 1 vs Tier 2 results

The second part of the testing focused on validating the consistency of the model by comparing the outputs of Tier 1 and Tier 2 approaches. While Tier 1 uses only topsoil data, Tier 2 incorporates information from all soil horizons, allowing a more comprehensive and detailed evaluation. To perform this validation, two soil profiles were selected: one natural and one contaminated.

For the natural profile, the Tier 1 analysis was based on the first horizon (A horizon) extracted from the ESDAC database, which provides harmonized soil data across Europe. For the Tier 2 analysis, the same soil profile was assessed using all available horizons (A, B, and C), allowing the model to capture variations across the soil profile. The selected soil is located in Spain and its land use is forestry. The ESDAC dataset is described in Section 2.4.

For the contaminated profile, the Tier 1 results were obtained using the original topsoil data provided by (Serrano-Garcia et al., 2025), which refer to an abandoned arsenic–copper mine in northern Spain. In contrast, Tier 2 required the construction of a hypothetical full soil profile. In this case, the A horizon values were retained, while B and C horizons were extrapolated based on literature values describing typical depth-related variations in contaminated soils (Gruszecka & Wdowin, 2013).

This phase aimed to verify the robustness and reliability of the Tier 1 approach in cases where full soil profile data are not available, by checking the degree of agreement between the two tiers. A partial anticipation of expected outcomes includes confirming whether Tier 1 alone is sufficient to provide meaningful and coherent soil quality assessments, especially when applied to contrasting land conditions.

The results of both testing phases will be presented and discussed in Chapter 3, with a focus on identifying key trends and differences in soil quality scores across the different land conditions evaluated. Particular attention will be given to the model’s ability to

distinguish between natural and degraded soils using Tier 1 data, as well as to the consistency between Tier 1 and Tier 2 outputs.

2.4 Data and document sources

The methodological basis and structure of the soil quality assessment model are based on the internal documentation revised and produced during the project. This includes the selection of relevant soil functions in the context of mining, the list of descriptors and their thresholds, and the algorithm used to translate input data into functional performance scores.

The Soil Survey and Health Conservation Management Plan (SSHCMP) supporting the conceptual model has been developed drawing on a wide body of European research in the fields of soil degradation, ecological restoration, and mining impacts. Particular emphasis was placed on studies analyzing the environmental impacts on soil and vegetation cover in real mining sites across Europe, with a significant proportion of the case studies located in Spain and conducted by various universities. Most of these researches were provided internally by the thesis supervisors. In addition to academic sources, the research was supported by scientific articles retrieved from platforms such as Google Scholar, the PICO database (which provides access to articles, books, and journals from the Politecnico di Torino), and Perplexity, an AI-powered tool that helps identify reliable sources based on the topic in question. A substantial portion of the information and technical recommendations was gathered from López Jimeno (2020), a reference book on aggregates excavation and site restoration.

The data used to test the model were obtained from two different sources: one for natural soils across Europe, and another for the soil of an abandoned contaminated mine in the north of Spain.

For natural soils, data were obtained from the LUCAS (Land Use/Cover Area frame Survey) Topsoil 2018 dataset, following a formal request through institutional credentials. LUCAS is an initiative of the European Commission aimed at monitoring land use and cover changes across the EU. Since 2009, the survey has been expanded to

include systematic soil sampling and analysis, with the goal of creating a harmonized, geo-referenced database of topsoil characteristics across Member States.

The LUCAS Topsoil survey represents the first consistent pan-European effort to assess soil properties using standardized field sampling and laboratory protocols. In the 2018 campaign, soil samples were collected at approximately 20,000 locations across 25 EU countries, including additional data from Malta and Cyprus. Samples were taken from the top 0 - 20 cm of soil and analyzed in a single reference laboratory to ensure consistency and comparability. The resulting database contains measurements of a wide range of parameters, including:

- Particle size distribution (clay, silt, sand)
- pH (in both H₂O and CaCl₂)
- Organic carbon
- Phosphorus and total nitrogen
- Bulk density
- Cation exchange capacity, carbonates, and coarse fragments

For the purposes of this study, a subset of LUCAS Topsoil 2018 data was selected, focusing on the variables most relevant to soil quality evaluation: pH in H₂O, organic carbon, nitrogen (N), phosphorus (P), bulk density, and particle size distribution. Only samples with a complete set of descriptors were retained and used to construct representative natural soils.

For the Tier 2 testing, data from the European Soil Data Centre (ESDAC) were used. The ESDAC dataset, which is older than LUCAS database and includes surveys conducted between the early 1990s and mid-2000s (depending on the country and sampling campaign), provides a more detailed dataset that includes multiple soil horizons per profile. The database offers a wide range of measured soil properties, including pH, organic carbon, nitrogen, phosphorus, bulk density, and particle size distribution, among others. These measurements are structured by horizon, making it possible to reconstruct full soil profiles with individual layers (see Section 1.1.1).

Although the ESDAC data are not recent, they remain valid for the purposes of this study, as the objective of the Tier 2 evaluation is not to assess temporal trends in soil quality but rather to compare the output of the model when using a full-profile, horizon-based

assessment (Tier 2) versus a simplified topsoil only analysis (Tier 1). The availability of multi-horizon data in ESDAC makes it a valuable resource for testing the consistency and sensitivity of the model across both methodological tiers.

For the degraded soils, the data were provided by the thesis supervisor and originate from an abandoned and heavily contaminated copper–arsenic mining site located in the province of Palencia, in northern Spain. This site has been the subject of prior scientific investigations, including a recent Screening-Level Ecological Risk Assessment (SLERA) study (Serrano-García et al., 2025), and is characterized by significant environmental degradation due to past mining and processing activities. The study area is divided into three main zones: the primary mining zone, the area surrounding a seasonal creek that drains into a nearby river, and the site of the former processing plant. Soil samples from these zones were analysed for pH, organic matter content, and concentrations of potentially toxic elements, particularly arsenic (As) and copper (Cu), which are present in very high concentrations. The results highlighted the presence of significant contamination hotspots and the importance of edaphic factors, particularly low pH and organic matter content, in influencing metal availability and the potential for plant recolonization. These data provided a realistic and complex example of degraded soils and were instrumental in testing the model's capacity to assess soil health in post-mining environments.

Finally, the regulatory framework was defined based on current European legislation, as explained in details in Section 1.3. The Nature Restoration Regulation (Regulation EU 2024/1991) and the Directive on Soil Monitoring and Resilience were used to frame the importance of soil quality in the wider context of land management and restoration in Europe.

2.4.1 Data preparation

For proper testing and analysis (described in Section 2.4), different data for computing both Tier 1 and Tier 2 were required.

To apply the model using the Tier 1 approach, a specific set of indicators was required, each corresponding to a key physical, chemical, or biological property of the topsoil (0–

20 cm). The selected indicators, their units, and the methodology used for data retrieval and adjustment are summarized in Table 19.

For natural soils, data were primarily derived from the LUCAS Topsoil 2018 dataset, as described in Section 2.3. In a few cases, such as erosion rates or saturated hydraulic conductivity, values were not directly available in the database and were instead estimated based on auxiliary references (e.g., climate-land use combinations or soil texture classes).

For degraded soils, the indicators were compiled from field data collected at the abandoned mining site (see Section 2.3) and supplemented with literature-derived values where direct measurements were missing. In some cases, such as bulk density or phosphorus content, average values from mining and quarrying land uses within the LUCAS dataset were used as proxies, due to the lack of site-specific measurements.

Table 18 – Indicators used for Tier 1 input and methods of data adjustment

Indicator	Unit	Natural Soils (LUCAS)	Degraded Soils (Mining Site)
Soil Depth	cm	Assumed depth of 40 cm to allow comparison	Assumed depth of 40 cm to allow comparison
Soil Texture	%	Derived from LUCAS; USDA texture triangle (Fig. 2)	Average values from LUCAS soils classified as "mining and quarrying"
pH	–	Taken directly from LUCAS	Taken directly from field measurements
Organic Matter (OM)	SOC/clay ratio	SOC from LUCAS (g/kg) converted to % and divided by clay %	OM expressed in %, divided by clay %
Erosion Rate	t ha ⁻¹ y ⁻¹	Estimated using values from Xiong & Chen (2019) based on land use and climatic region	Estimated using values from Xiong & Chen (2019) based on land use and climatic region
Bulk Density	g cm ⁻³	Taken directly from LUCAS	Average values from LUCAS soils in mining and quarrying land use
Nitrogen (N)	g kg ⁻¹	Taken directly from LUCAS	Average values from LUCAS soils in mining and quarrying land use
Phosphorus (P)	g kg ⁻¹	Taken directly from LUCAS	Average values from LUCAS soils in mining and quarrying land use
Saturated Hydraulic Conductivity	cm d ⁻¹	Estimated from soil texture using Sarki et al. (2014)	Estimated from soil texture using Sarki et al. (2014)
Retention Capacity	% (w/s)	Set to upper limit value (25%)	Set to upper limit value (25%)
Trace Element Concentration	mg kg ⁻¹	Set to 0 (assuming non-contaminated conditions)	Concentration taken directly from field measurements

For the Tier 2 evaluation, which involves the reconstruction of full soil profiles based on horizon-specific information, a different approach was followed for natural and degraded soils.

For natural soils, all indicators were obtained from the European Soil Data Centre (ESDAC) database, which provides open-access soil profile data from various European regions. Soil depth was calculated by summing the thicknesses of horizons A, B, and C. Texture classification was derived using the USDA soil texture triangle based on particle size distribution data. Other indicators such as bulk density, pH, organic matter (OM),

nitrogen (N), and phosphorus (P) were taken directly from the database. The erosion rate was estimated using the same reference applied in Tier 1 (Xiong & Chen, 2019) while retention capacity was again fixed at 25%, and trace element concentrations were assumed to be zero, under the assumption of uncontaminated conditions.

For contaminated soils, the A horizon values were based on actual data from the mining site and aligned with LUCAS indicators used in Tier 1. For deeper horizons (B and C), values were reconstructed using literature-based trends, as no field measurements were available. In particular, data from Gruszecka & Wdowin (2013) were used to estimate the vertical decrease in heavy metal concentrations with depth, while maintaining pH relatively stable, in line with general ESDAC trends. OM, N, and P concentrations were reduced progressively in deeper layers, following typical patterns described in the same source. These estimations allowed for the simulation of a plausible, depth-differentiated soil profile for use in Tier 2 assessment.

Table 19 – Indicators used for Tier 2 input and methods of data adjustment

Indicator	Unit	Natural Soils (ESDAC)	Degraded Soils (Mining Site)
Soil Depth	cm	Sum of the thicknesses of A, B, and C horizons	Sum of the thicknesses of A, B, and C horizons
Soil Texture	%	Derived from particle size distribution using USDA texture triangle	A horizon from LUCAS; B and C horizons estimated using ESDAC patterns
pH	–	Taken directly from ESDAC	A horizon from mining data; B and C horizons assumed stable based on ESDAC trends
Organic Matter (OM)	SOC/clay ratio	Taken directly from ESDAC	A horizon from field data; OM reduced in deeper layers based on Gruszecka & Wdowin (2013)
Erosion Rate	t ha ⁻¹ y ⁻¹	Estimated using Xiong & Chen (2019) based on land use and climatic region	Estimated using Xiong & Chen (2019) based on land use and climatic region
Bulk Density	g cm ⁻³	Taken directly from ESDAC	A horizon from LUCAS; B and C estimated based on typical depth trends
Nitrogen (N)	g kg ⁻¹	Taken directly from ESDAC	A horizon from data; N reduced in deeper layers as in Gruszecka & Wdowin (2013)
Phosphorus (P)	g kg ⁻¹	Taken directly from ESDAC	A horizon from data; P reduced in deeper layers as in Gruszecka & Wdowin (2013)
Saturated Hydraulic Conductivity	cm d ⁻¹	Estimated from soil texture using Sarki et al. (2014)	Estimated from soil texture using Sarki et al. (2014)
Retention Capacity	% (water/soil)	Set to upper limit value (25%)	Set to upper limit value (25%)
Trace Element Concentration	mg kg ⁻¹	Set to 0 (non-contaminated)	A horizon from field data; B and C values reduced with depth following Gruszecka & Wdowin (2013)

Among the potentially toxic elements considered in the contaminated soils, arsenic (As) was identified as the primary risk element, both due to its toxicological relevance and its markedly elevated concentrations observed in the sampling zones. Arsenic is a well-known carcinogenic and mutagenic metalloid, persistent in the environment and capable

of accumulating in soil, plants, and groundwater, posing long-term risks to both ecosystems and human health.

To assess the severity of arsenic contamination and support the interpretation of model outputs, it was necessary to identify a Soil Screening Level (SSL) for arsenic as a reference threshold. In the Spanish regulatory framework, SSLs are referred to as “Niveles Genéricos de Referencia (NGR)”. While for organic and inorganic compounds the national reference levels are unified under the Real Decreto 9/2005, the NGRs for metals and metalloids are established independently by each Autonomous Community.

In the case of the contaminated site under study, located in Castilla y León, no official NGRs for metals (including arsenic) have been published to date. Therefore, for the purposes of this study, the NGR established by the nearest Principality of Asturias has been adopted as a suitable reference. Table 21 presents the NGRs for the metals identified at the site, based on the values established in the *Resolución de 20 de marzo de 2014* by the Principality of Asturias, for the “other uses” category.

Table 21 – SSL of the metals found with high concentrations on the site

Element	SSL for other uses (mg/kg)	
	General	Soils over calcareous lithology
Arsenic	40	100
Cadmium	2	10
Copper	55	55
Chromium (III)	10000	10000
Nickel	65	65
Lead	70	70
Zinc	455	455

According to the Resolución de 20 de marzo de 2014, which defines regional NGRs based on land use, the threshold for arsenic in soils designated for “other uses” (i.e., uses other than residential, recreational, or industrial) is set at 40 mg/kg. However, this threshold is raised to 100 mg/kg when the soils are developed over calcareous lithologies. According to the MAGNA50 geological map (sheet 107) by IGME (Instituto Geológico y Minero de España), the studied soils lie over calcareous formations. Therefore, the SSL value was set at 100 mg/kg for all contaminated soils. This threshold was used in the assessment to contextualize the Tier 1 and Tier 2 model results, as arsenic concentrations exceeded the NGR values in every soil sample, identifying arsenic as the primary risk element.

3 Results and Discussion

This chapter presents the results obtained by applying the soil quality evaluation system developed in the SSHCMP. As explained in the previous sections, the model was tested using real soil data, both from natural soils and from a contaminated site. The goal of this part is to understand whether the model is able to distinguish between soils in good condition and those that are more degraded or polluted.

The chapter is divided into two main parts. The first one focuses on the comparison between natural and degraded soils, using the Tier 1 method, which evaluates only the topsoil (0 - 20 cm). The second part looks at the consistency of the model, comparing the results obtained using Tier 1 (topsoil only) and Tier 2 (all soil horizons).

3.1 Natural and degraded soils results

This section presents the results of the soil quality model applied to two contrasting soil types: natural and contaminated soils. The aim is to evaluate how different land conditions influence the performance of key soil functions. Scores were calculated using the Tier 1 approach and are shown in Table 22 for natural soils and Table 23 for contaminated soils. The comparison highlights the main differences in soil health and helps identify which functions are most affected by degradation.

Table 22 – Tier 1 results of natural soils

Natural soils	N1	N2	N3	N4	N5	N6	N7	N8	N9	Mean	St.dev.
Organic Recycling	1,67	2,33	1,33	1,67	2,00	2,33	2,33	2,33	2,33	2,04	0,37
Erosion	3,00	3,00	3,00	3,00	3,00	3,00	0,00	0,00	0,00	2,00	1,41
Carbon Storage	2,50	2,50	2,50	2,50	2,50	2,50	2,50	2,50	2,50	2,50	0,00
Fertility	1,80	2,00	2,20	1,80	2,00	1,80	2,00	2,20	2,00	1,98	0,15
Water retention	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	0,00
Water infiltration	2,50	2,50	1,50	2,00	1,50	2,50	2,50	2,50	2,50	2,22	0,42
Contamination	2,33	2,67	2,00	2,33	3,00	2,67	2,67	2,67	2,67	2,56	0,27

Table 23 - Tier 1 results of contaminated soils

Contaminated soils	D1	D2	D3	D4	D5	D6	D7	D8	D9	Mean	St.dev.
Organic Recycling	1,00	2,67	2,00	1,33	1,67	1,00	1,00	1,00	1,00	1,41	0,56
Erosion	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Carbon Storage	1,00	1,50	1,00	2,50	1,00	1,00	1,00	1,00	1,00	1,22	0,48
Fertility	0,80	1,40	1,40	0,80	1,20	0,80	0,80	0,80	0,80	0,98	0,26
Water retention	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	0,00
Water infiltration	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	0,00
Contamination	0,00	0,00	0,00	0,00	2,33	0,00	0,00	0,00	0,00	0,26	0,73

The Tier 1 comparison between natural and contaminated soils revealed a clear overall trend: natural soils consistently outperformed contaminated soils across all evaluated functions. This reflects not only the lower degree of anthropogenic disturbance in natural sites, but also their higher functional capacity and ecological resilience. Figure 11 presents a radar chart illustrating the mean scores of each soil function for both contaminated and natural soils. This visual representation highlights the average performance of the two soil groups across all evaluated functions.

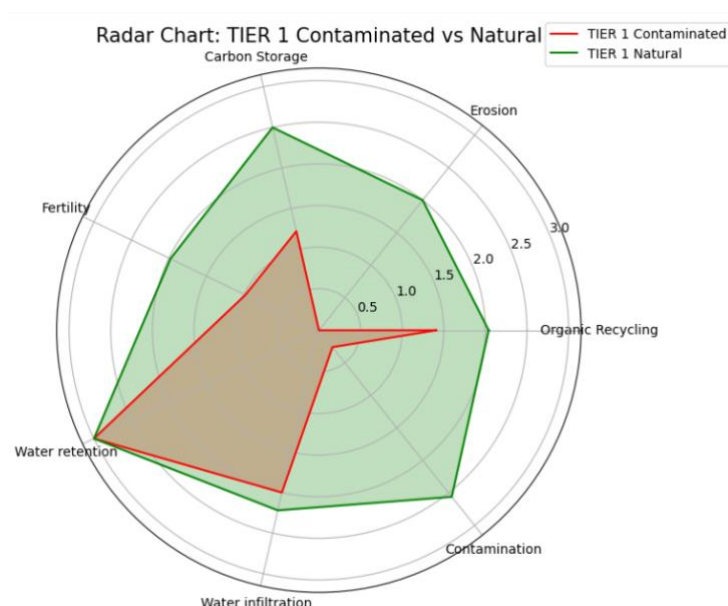


Figure 11 – Radar Chart with comparison between the average of two soil groups: contaminated in red and natural in green.

Among the most distinctive differences, the Contamination function shows a strong contrast. Natural soils display high contamination scores (mean 2.56, min 2.00, max 3.00), reflecting the absence of trace element pollution. In contrast, the contaminated soils exhibit critically low values (mean 0.26, min 0.00, max 2.33), as expected due to high arsenic concentrations in the mining site. This function was calculated based on pH, arsenic concentration, and soil depth, and its low scores indicate the soil's limited ability to buffer or immobilize toxic elements, which is an aspect likely tied to reduced organic matter (Guía de investigación de la calidad del suelo), pH acidity or alkalinity (Arranz-González, 2011).

Similarly, the Erosion function shows a dramatic gap between the two groups. While natural soils present a wide range of values (0 to 3), with a mean of 2.00 (min 0.00, max 3.00), all contaminated soils received a score of 0. This is not due to low erosion risk, but rather to the classification of mining and industrial soils as bare land in the Xiong & Chen (2019) model. Bare land is assigned the highest erosion rates, reflecting the severe degradation and lack of vegetative cover in such environments. On the other hand, natural soils N7, N8, and N9 (despite being classified as “natural”) showed erosion scores of 0.00, due to their agricultural land use and likely lack of ground cover, emphasizing that land management can significantly affect soil resilience even in non-contaminated contexts.

The Carbon Storage function also shows strong differences: natural soils reached consistently high values (2.50 in all cases), while contaminated soils had significantly lower and more variable scores (mean 1.22, min 1.50, max 2.50). This result is consistent with lower organic matter content and possibly different clay content in the mining soils. Interestingly, the only contaminated soil with a relatively high score (2.50) was D4, located near the seasonal creek, where local hydrological conditions or sediment accumulation may enhance carbon inputs and organic matter distribution (Puerta Angulo, 2015).

Fertility is another function that shows a clear difference between the two soil groups. Natural soils achieved relatively high scores, with a mean of 1.98 (min 1.80, max 2.20), suggesting sub-optimal but generally healthy fertility levels. In contrast, contaminated soils had a significantly lower mean of 0.98 (min 0.80, max 1.40), indicating a degraded condition. This difference is likely related to the low nutrient content (particularly

nitrogen and phosphorus), suboptimal pH levels, and poor structural properties typical of post-mining soils. Importantly, none of the samples, reached the maximum score. This is due to the way the fertility score is calculated: it is based on six parameters (bulk density, nitrogen, phosphorus, pH, texture, and soil depth), so even one limiting factor is enough to reduce the overall score. This reflects the sensitivity of the fertility function and the difficulty of achieving optimal conditions across all contributing soil properties.

The Organic Recycling function, driven by soil depth, pH and organic matter, also revealed a degraded status in contaminated soils (mean 1.41, min 1.00, max 2.67), compared to healthier values in natural soils (mean 2.04, min 1.33, max 2.33). However, some variability was observed within the contaminated group. Notably, sample D2 scored 2.67 (see Figure 12), which is relatively high. This can be explained by its favorable characteristics: among the 27 available degraded soil samples, this one had a higher organic matter value and a neutral pH, justifying its inclusion to represent internal heterogeneity in the degraded dataset. In fact, the study by Pérez et al. (2012) highlights how mine soils are severely degraded, particularly in terms of pH and organic matter content, two key factors that critically influence the processes governing organic matter cycling and overall soil health.

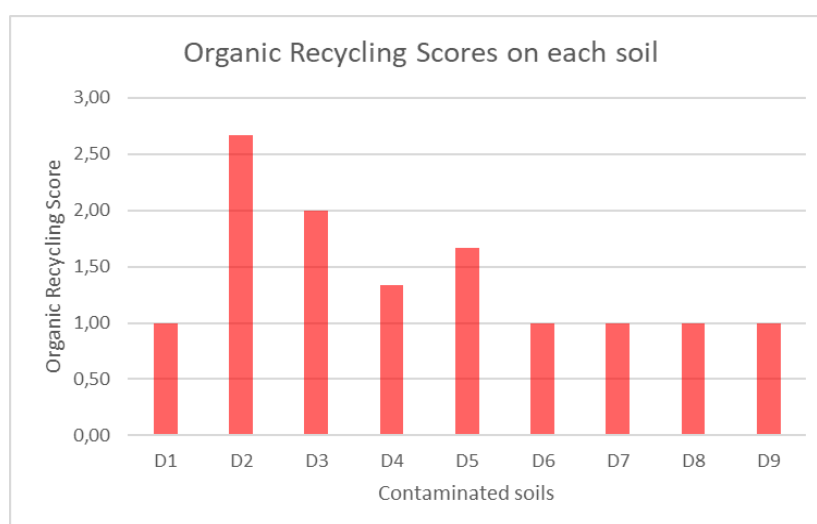


Figure 12 – Representation of the heterogeneity among all soil samples concerning Organic Recycling function

Regarding Water Infiltration, both soil types showed relatively high and stable values (mean 2.22, min 1.50, max 2.50 in natural soils and mean 2.00 in all contaminated soils), with only slightly lower performance in the latter. This function was estimated based on

saturated hydraulic conductivity (K_{sat}), calculated from soil textures in the study conducted by Sarki et al. (2014). As such, it may not fully reflect the behaviour of the mining soils in study, but it still suggests that mining soils may retain some infiltration capacity. This may be due to soil compaction typically caused by heavy machinery in mining areas, which significantly reduces porosity and limits the soil's ability to exchange air and water, thereby affecting its infiltration dynamics.

Finally, the Water Retention function obtained maximum scores (3.00) for all samples, regardless of soil condition. This uniformity is due to the methodological choice of setting retention capacity at its upper threshold for both groups, to avoid underestimating this function in the absence of direct data. As a result, no real differences can be inferred, and this function should be interpreted with caution in this context.

3.1.1 Discussion and use of the model

The following section discusses in greater detail the trends observed, with a focus on the most sensitive functions and the potential implications of the model in management and restoration planning.

An aspect that stands out, is the influence of pH and organic matter on soil functions in contaminated soils. Several key soil functions, like Organic Recycling, Carbon Storage and Fertility, depend strongly on soil pH and organic matter content. In this study, the contaminated soils scored low for these functions. For example, studies on mine-affected soils (Pérez et al., 2012) show that these soils usually have very low organic matter and often extreme pH value. Such conditions negatively affect the activity of soil microorganisms, which are essential for breaking down organic material and cycling nutrients. When carbon content and nutrient decline, it leads to a soil with poor fertility and reduced capacity for organic matter recycling, since the soil is limited on the revegetation process (Quintas & Macias, 1992). This explains why contaminated soils in our study performed worse than natural soils in these functions. As an example, Figures 13 and 14 illustrate the relationship between Organic Matter content and the scores of the Organic Recycling and Fertility functions. As shown, higher Organic Matter values generally correspond to higher function scores, although both functions also depend on other soil descriptors.

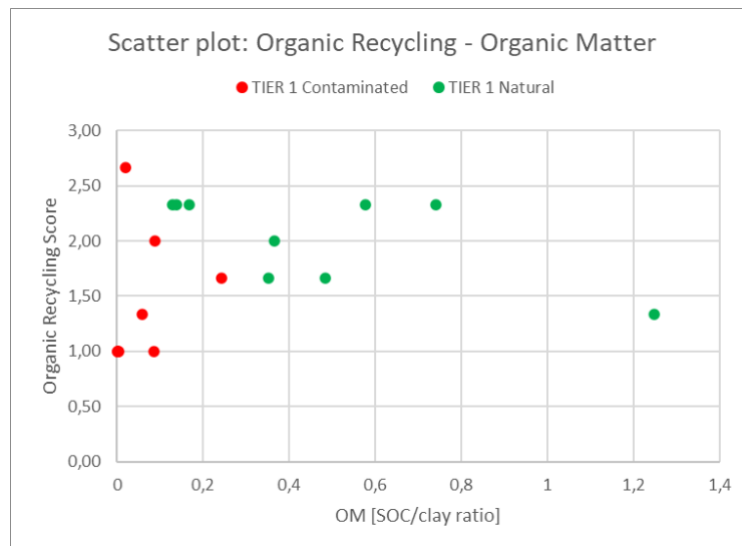


Figure 13 - Scatter plot between the Organic Recycling Score and the Organic Matter content in natural and contaminated soils

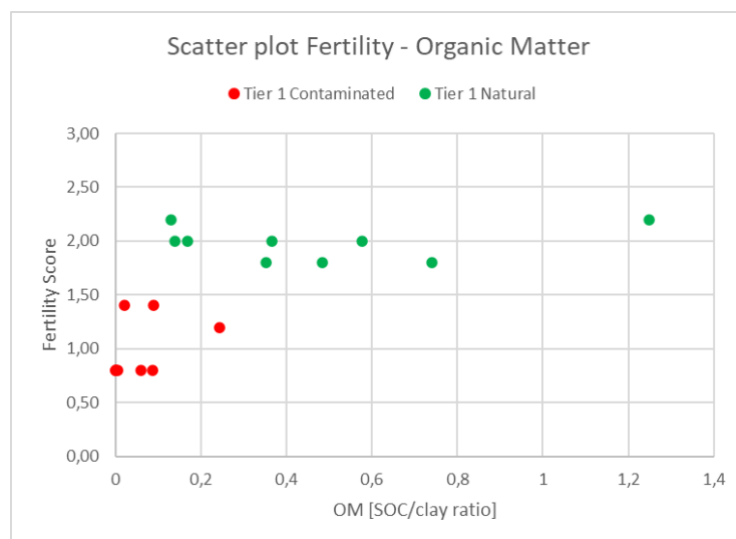


Figure 14 – Scatter plot between the Fertility Score and the Organic Matter content in natural and contaminated soils

Among all functions, fertility and contamination appear to be the most sensitive based on the results of this study. Fertility is strongly affected by variation in pH, nutrient availability, and organic matter and it is very susceptible to degradation. Contamination in polluted areas, provides critical insights about the presence and mobility of toxic elements such as arsenic and should be closely monitored to avoid risks for human and ecological health.

Although the general trend shows that contaminated soils are in a critically degraded state for most functions, it is important to note that not all samples perform the same. For example, sample D2 scored much higher than the others in the Organic Recycling function (2.67, compared to the group average of 1.41). This is likely due to better conditions in that sample, such as higher organic matter content and a more favorable pH, which support microbial activity and the decomposition of organic material.

This kind of variability is common in post-mining areas (Arranz-González, 2004a), where soil characteristics can change a lot from one point to another depending on contamination levels, past land use, and landscape features. These differences affect how well each soil can perform its ecological functions. Because of this, it is useful to include a variety of samples when testing the model, as done in this study. This helps to better understand the complexity of degraded areas and shows that local conditions must be considered when planning restoration actions or risk assessments. It also suggests that average values alone may hide important differences between soils in the same area.

The results of this first comparison confirm the model's potential to evaluate the functional condition of soils in mining contexts. However, beyond the ability to distinguish between natural and degraded conditions, a key question is when this tool should be applied during the mining cycle, and how it can support decision-making.

The model should ideally be applied during the pre-extraction phase, before any disturbance occurs (Module I). This is the moment to assess the natural functional profile of the soil. While not all functions need to score highly, since soils naturally vary in their ecosystem roles, it is crucial to understand and preserve their initial balance. Maintaining or improving the baseline condition is essential, and efforts should be taken to avoid any significant functional loss.

A second key moment for application is during the soil storage phase. In this phase, the model can serve as a monitoring and reference tool, helping to ensure that soil health is not progressively degraded during stockpiling (Module II). Lastly, comparing the post-storage condition with the pre-disturbance state can provide valuable insights for guiding appropriate management and conservation strategies in the post-extraction phase, offering an instrument for deciding when and how to implement corrective actions (Module III).

The model also supports the decision on when to implement corrective measures. A clear threshold is given by the functional scores: if the same soil that initially showed values above 1.50 begins to show scores below this threshold, it is an indication that restoration or mitigation actions may be necessary. Moreover, the level of each function should be interpreted based on the intended land use after closure. For example, if the post-mining use is agricultural, special attention must be paid to fertility and contamination, which should ideally be in a healthy or at least sub-optimal condition to ensure safe and productive use.

In conclusion, this first comparison highlights the model's ability to differentiate soil conditions based on functions' performance. Natural soils exhibit significantly better results in all functions, with particular strength in contamination buffering, carbon storage, and erosion resistance. In contrast, contaminated soils show critical or degraded status in these same functions, underscoring the severity of degradation in post-mining environments. Functions such as fertility and organic recycling appear moderately affected, while water-related functions (infiltration and retention) show more uniform values, likely due to methodological estimations. These findings support the utility of the Tier 1 approach in capturing key aspects of soil health, even when working with limited surface data.

3.2 Tier 1 vs Tier 2 results

The comparison between Tier 1 and Tier 2 was performed on two selected soil profiles: one contaminated and one natural. The aim was to test the coherence between the simplified Tier 1 approach (topsoil only) and the more complete Tier 2 approach (full profile), and to evaluate whether Tier 1 provides reliable results when data availability is limited. The outputs of both tiers of natural soils are presented in Table 24 and the ones of contaminated soils are presented in Table 25.

Tables 24 and 25 – Scores of both Tier 1 and Tier 2 for natural and contaminated soil

	Natural Soil			Contaminated Soil	
	TIER 1	TIER 2		TIER 1	TIER 2
Organic Recycling	1,67	1,74	Organic Recycling	1,00	1,66
Erosion	3,00	3,00	Erosion	0,00	0,00
Carbon Storage	1,50	1,50	Carbon Storage	0,50	1,11
Fertility	1,40	1,45	Fertility	0,80	1,19
Water retention	3,00	3,00	Water retention	3,00	3,00
Water infiltration	2,00	2,00	Water infiltration	1,50	2,00
Contamination	3,00	2,82	Contamination	0,00	0,00

In general, the results show a high degree of consistency between the two approaches for both soils. The Tier 2 scores are slightly higher in most functions, especially in the contaminated soil. This confirms the expectation that Tier 1 is not only a simplified version of the model but also a more conservative one, which tends to produce lower scores in uncertain contexts. In Figure 15 and 16 a graphical view of the results is shown.

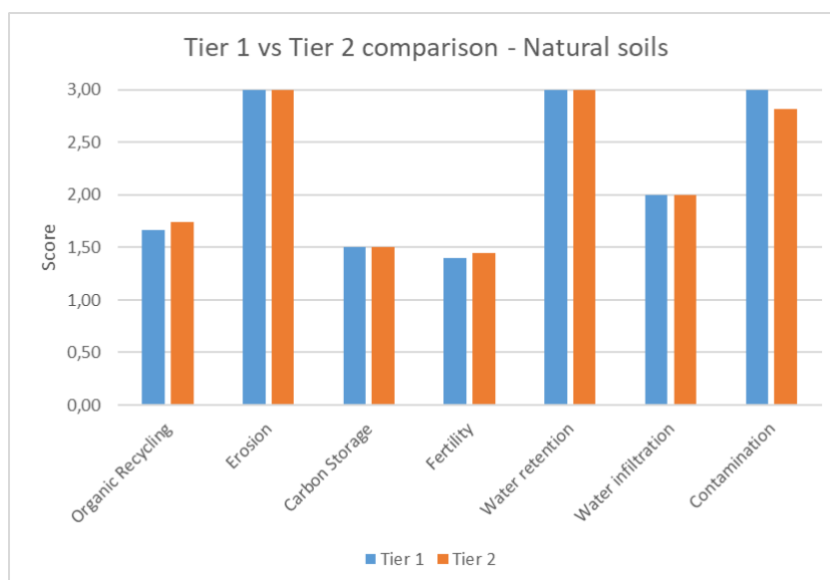


Figure 15 – Comparison between Tier 1 and Tier 2 in Natural soils

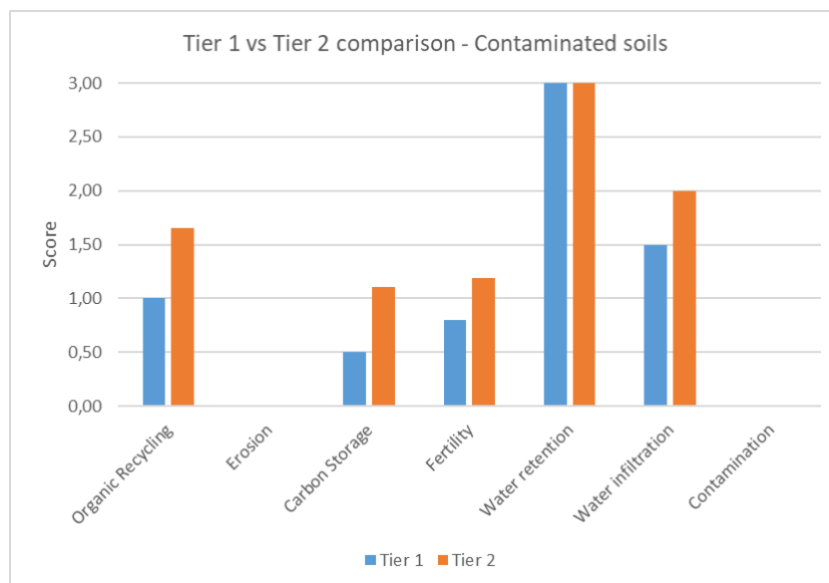


Figure 16 - Comparison between Tier 1 and Tier 2 in Contaminated soils

For the natural soil, the scores remained nearly identical between Tier 1 and Tier 2 in all functions, except for a slight decrease in Contamination (from 3.00 to 2.82), likely due to small pH variations along the profile. The stability of scores reflects the homogeneity of natural soils and reinforces the idea that Tier 1 provides a sufficiently accurate representation when no deep contamination or sharp stratification is expected. This result also confirms the consistency and robustness of the Tier 1 model in healthy soil conditions.

For the contaminated soil, Tier 2 shows visible improvements in key functions such as Organic Recycling (from 1.00 to 1.66), Carbon Storage (from 0.50 to 1.11), Fertility (from 0.80 to 1.19), and Water Infiltration (from 1.50 to 2.00). These increases are due to the influence of deeper horizons, even if these were modeled based on literature values. In fact, as described in Section 2.4.2, organic matter, nitrogen, phosphorus, and metal concentrations were strongly reduced in the B and C horizons, while pH was kept relatively stable along the profile, as reported in the study Gruszecka & Wdowin (2013).

Even though OM and nutrients decreased sharply with depth, the addition of these horizons contributed to raise the final Tier 2 score due to the Functional Relevance Factor applied in the model (see Table 18 in Section 2.2.2): for instance, in the case of Organic Recycling, the relevance is 1 for horizon A, but still 0.6 and 0.2 for B and C respectively, allowing some contribution from deeper soil.

The Water Infiltration function increased in Tier 2 not because of changes in soil texture (which remained the same across the profile), but due to the higher soil depth used in the calculation. While Tier 1 was based on a conservative assumption of 40 cm depth, Tier 2 considered 90 cm, according to data from (Gruszeckac & Wdowin, 2013). This highlights the role of depth in infiltration potential, particularly relevant for post-mining restoration where compacted layers often reduce soil functionality.

In contrast, the Contamination scores remained unchanged in the contaminated profile, confirming the severe degradation already identified at the topsoil level. The fact that no improvement was observed in the Tier 2 results suggests that contamination levels are critically high, even though arsenic concentrations were reduced by more than half in the deeper soil horizons.

Similarly, erosion scores remained unchanged, as this function is only assessed in the uppermost layer (Horizon A), which is the only part of the soil profile directly exposed to natural and anthropogenic erosion processes.

Conclusions

This thesis was framed at supporting the implementation of European strategies developed for soil health and conservation in mining, in the context of supporting Goal 4 of the ROTATE project, which is aimed at restoring mining areas and conserving biodiversity. The approach developed was intended to be used to assess soil quality and ensure that soil attributes are maintained over time throughout the stages of mining activity: from pre-exploitation to post-mining rehabilitation.

For doing this, the model was applied to a variety of natural and contaminated soil data from Europe (LUCAS and ESDAC) and to data from a former mining site located in north Spain. Results indicated that the model is able to differentiate natural and degradation soils in terms of the performance of the different soil functions. As anticipated, natural soils achieved markedly higher scores (average: 2.33) than contaminated soils (average: 1.27) on all three sites. The most sensitive and meaningful values of some functions (Fertility, Organic Recycling, and Contamination) were highlighted, particularly in post-mining areas, since they are crucial for ecological recovery according to degradation and prevention of health risks.

Another objective of the thesis was to evaluate if Tier 1, with data based only on the topsoil, was enough to provide reliable results when compared to Tier 2, with data reference to all soil horizons. In comparison with Tier 2, we found that Tier 1 results are very close and more conservative. This indicates that Tier 1 may be used as a suitable and efficient method where access to the lower depths of the soil is limited due to time, financial or practical constraints.

However, this model has some deficiencies even though the results are promising. In particular for the contaminated profile, the deeper horizons (B and C) needed to be constructed from literature, as no field data were available. This adds some ambiguity to the Tier 2 outcome. Furthermore, the model has been neither applied in a real pre-mining site when a mining project is in planning or operation stages, which restricts the model validation in dynamic or transitional conditions.

Future applications should focus on testing the model in active or planned mining sites, starting from the pre-extraction phase, to monitor the natural state of the soil before disturbance. This would allow for the preservation of key functions and the detection of early signs of degradation. Moreover, incorporating the model into soil storage monitoring would help ensure that stockpiled soils do not lose their functional integrity over time. Ultimately, this would support more targeted and effective restoration actions in the post-extraction phase.

In summary, the method provides an applicable and integrated approach to assessing the health of soils under mining land use. If it was field-tested further and complete datasets were available then it has potential as a tool that could be adopted and promoted in routine soil management on mining and post-mining sites throughout EU member states.

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Annex A – Descriptors value ranges corresponding to each score level

Table A1 – Soil descriptors involved in Recycling function and their scoring

Recycling Function				
Descriptor	Units	Score	Ranges	Key factor
Soil Depth	cm	0	< 5	Yes
		1	[5 - 10)	
		2	[10 - 20)	
		3	≥ 20	
pH	-	0	< 5	No
		1	[5 - 6)	
		2	≥ 7.5	
		3	[6 - 7.5)	
OM	SOC/clay ratio	0	< 1/13	No
		1	> 1/8	
		2	[1/13 - 1/10)	
		3	[1/10 - 1/8)	

Table A2 – Soil descriptors involved in Erosion function and their scoring

Erosion Function				
Descriptor	Units	Score	Ranges	Key factor
Erosion rate	t ha ⁻¹ y ⁻¹	0	≥ 50	Yes
		1	[20 - 50)	
		2	[10 - 20)	
		3	< 10	

Table A3 – Soil descriptors involved in Carbon storage function and their scoring

Carbon Function				
Descriptor	Units	Score	Ranges	Key factor
Soil Depth	cm	0	< 20	No
		1	[20 - 40)	
		2	[40 - 80)	
		3	≥ 80	
Horizon OM	SOC/clay ratio	0	< 1/13	No
		1	[1/13 - 1/10)	
		2	[1/10 - 1/8)	
		3	≥ 1/8	

Table A4 – Soil descriptors involved in Fertility function and their scoring

Fertility Function				
Descriptor	Units	Score	Ranges	Key factor
Soil Depth	cm	0	< 5	Yes
		1	[5 - 10)	
		2	[10 - 20)	
		3	≥ 20	
Horizon pH	-	0	< 5 V ≥ 8.5	No
		1	[5 - 6)	
		2	[7.5 - 8.5)	
		3	[6 - 7.5)	
Horizon N	g kg ⁻¹	0	< 2	No
		1	[2 - 10)	
		2	≥ 20	
		3	[10 - 20)	
Horizon P	g kg ⁻¹	0	< 0.04	No
		1	[0.04 - 0.08)	
		2	[0.08 - 0.12)	
		3	≥ 0.12	
Soil Texture (Sandy)	g cm ⁻³	0	> 1.80	Yes
		1	1.70 – 1.80	
		2	1.60 – 1.69	
		3	< 1.60	
Soil Texture (Loamy sands / Sandy loams)	g cm ⁻³	0	> 1.75	Yes
		1	1.61 – 1.75	
		2	1.40 – 1.60	
		3	< 1.40	
Soil Texture (Silts and silty clay loams)	g cm ⁻³	0	> 1.70	Yes
		1	1.56 – 1.70	
		2	1.35 – 1.55	
		3	< 1.35	
Soil Texture [Medium clays (35–45% clay)]	g cm ⁻³	0	> 1.58	Yes
		1	1.50 – 1.58	
		2	1.10 – 1.49	
		3	< 1.10	
Soil Texture [Pure clays (>45% clay)]	g cm ⁻³	0	> 1.47	Yes
		1	1.40 – 1.47	
		2	1.10 – 1.39	
		3	< 1.10	

Table A5 – Soil descriptors involved in Water Retention function and their scoring

Water Retention Function				
Descriptor	Units	Score	Range	Key factor
Soil Depth	cm	0	< 5	No
		1	[5 - 10)	
		2	[10 - 20)	
		3	≥ 20	
Retention capacity	% water / total soil	0	<10	Yes
		1	[10 - 15)	
		2	[15 - 25)	
		3	≥ 25	

Table A6 – Soil descriptors involved in Water infiltration function and their scoring

Water Infiltration Function				
Descriptor	Units	Score	Range	Key factor
Soil Depth	cm	0	< 20	No
		1	[20 - 40)	
		2	[40 - 80)	
		3	≥ 80	
Saturated Hydraulic Conductivity	cm d ⁻¹	0	< 0.86	Yes
		1	[0.86 - 8.64)	
		2	[8.64 - 86.4)	
		3	≥ 86.4	

Table A7 – Soil descriptors involved in Contamination response function and their scoring

Contamination Response Function				
Descriptor	Units	Score	Range	Key factor
Soil Depth	cm	0	< 5	No
		1	[5 - 10)	
		2	[10 - 20)	
		3	≥ 20	
Trace Elements	mg kg ⁻¹	0	> SSL (x5)	Yes
		1	[5x - 2x)	
		2	[2x - SSL)	
		3	≤ SSL	
Horizon pH	-	0	< 5	No
		1	[5 - 6)	
		2	[6 - 7.5)	
		3	≥ 7.5	

Annex B – Single Flowcharts for each of the seven functions

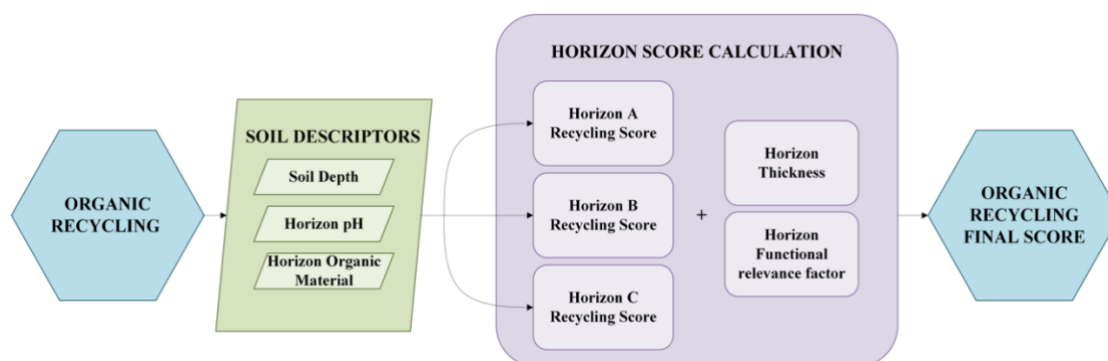


Figure B1 - Flowchart for assessing soil quality for Organic Recycling

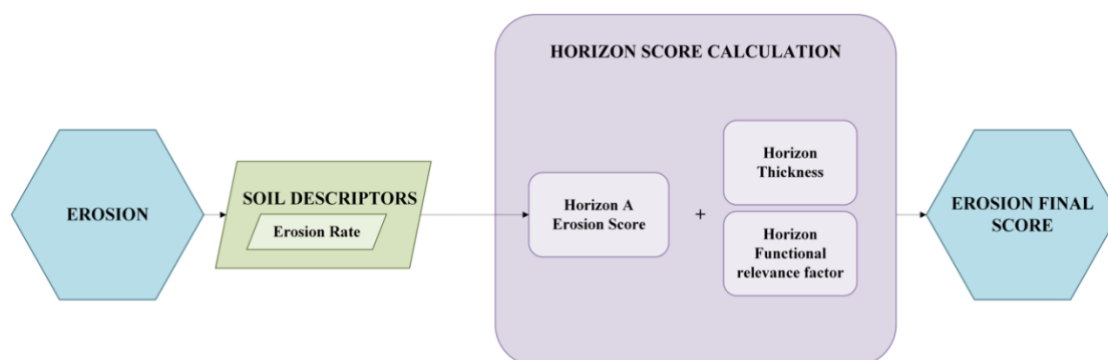


Figure B2 - Flowchart for assessing soil quality for Erosion

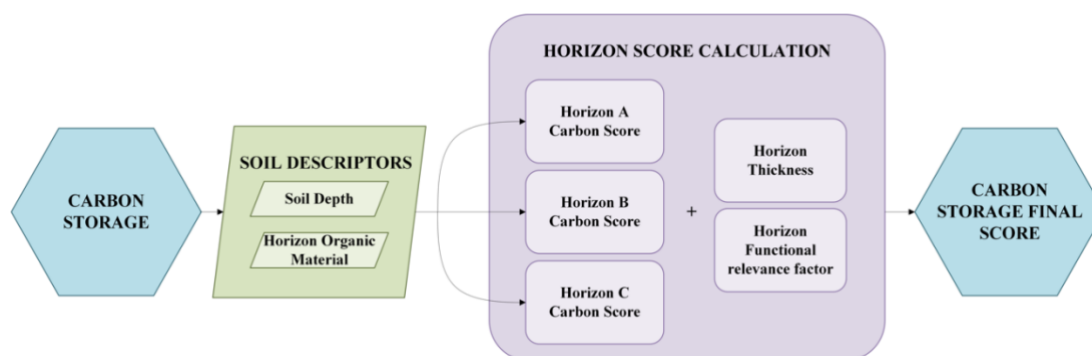


Figure B3 - Flowchart for assessing soil quality for Carbon Storage

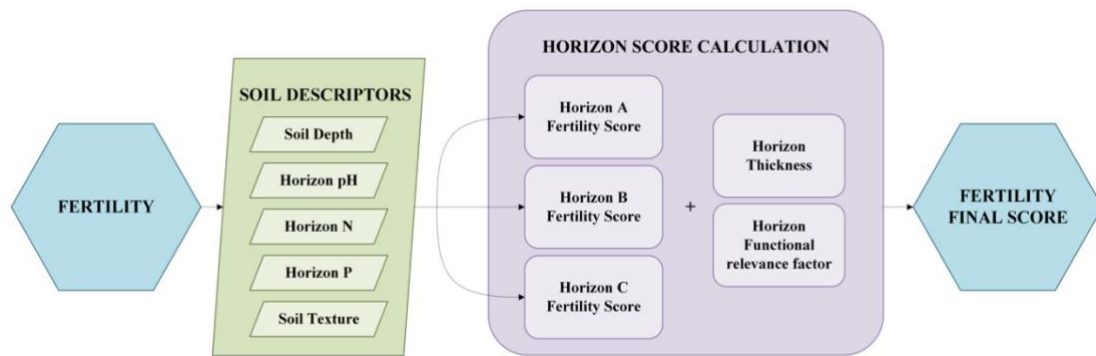


Figure B4 - Flowchart for assessing soil quality for Fertility

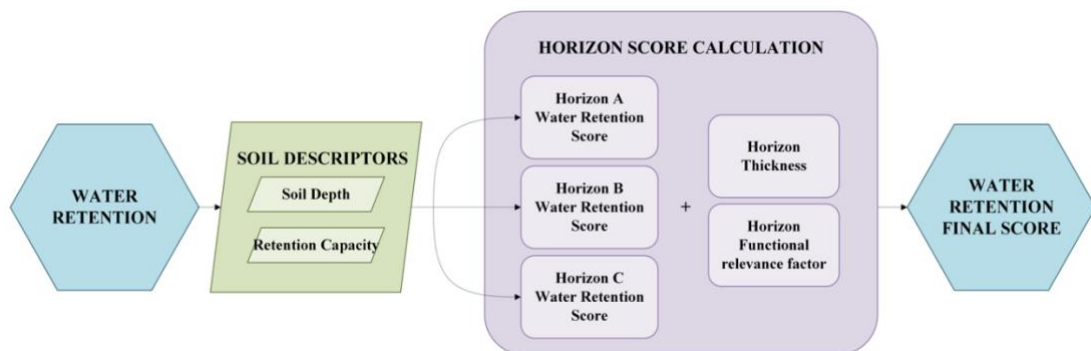


Figure B5 - Flowchart for assessing soil quality for Water Retention

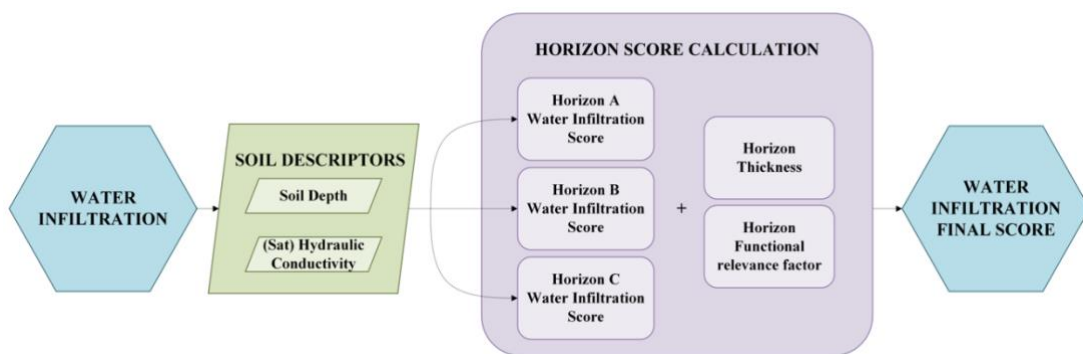


Figure B6 - Flowchart for assessing soil quality for Water Infiltration

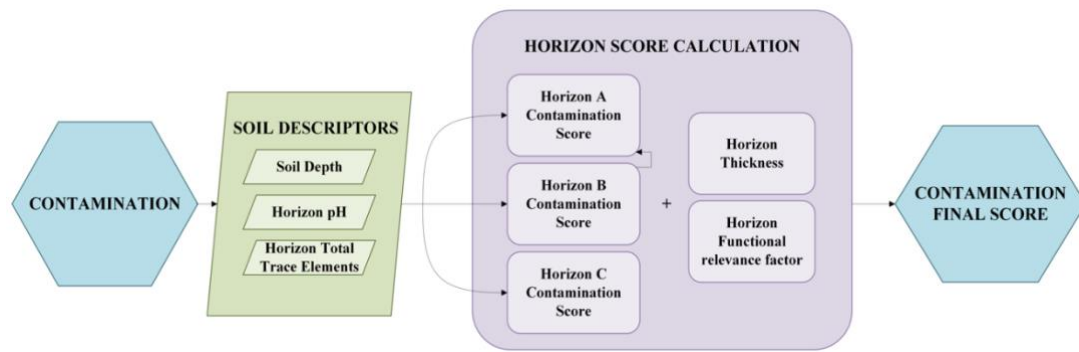


Figure B7 - Flowchart for assessing soil quality for Contamination