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PoLaRecCE

Annex I

Forms of land degradation defined by PoLaRecCE project

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Introduction

Soil degradation in many regions of Central Europe poses a serious threat to ecological stability, food security, and regional economies. Considering the EU territory as a whole, between 60% and 70% of land is considered unhealthy or affected by some form of degradation (Buckwell et al., 2022). For agricultural soils specifically, the estimated proportion is much higher—about 89% (Broothaerts et al., 2026). Central Europe (CE) is also a region subject to high degradation pressure. In CE, this problem results from a combination of a long history of mining and metallurgical activities, intensive large-scale agricultural practices, rapid economic transformation, climate change, and urban expansion. In Central Europe—perhaps more than in other European regions—current environmental conditions reflect the region's turbulent history and the associated long-term transformation of its landscapes. Currently, the dominant forms of soil degradation include water and wind erosion, soil compaction, loss of soil organic matter, contamination, and acidification. These processes contribute to reduced landscape water-retention capacity and declining biodiversity.

Historically, the EU Soil Thematic Strategy identified eight principal threats to soil: erosion, loss of organic matter, contamination, sealing, compaction, salinisation, landslides and flooding, and loss of soil biodiversity. More recently, the Soil Monitoring Law—Directive (EU) 2025/2360, which entered into force on 16 December 2025—established a common framework and soil descriptors for assessing soil degradation and soil health. The Directive adopts a more comprehensive approach than the earlier concept of a fixed list of "eight soil threats". Rather than defining a specific set of major soil degradation processes or threats, it uses measurable soil descriptors and criteria to assess soil condition, recognising that different degradation processes may interact (European Parliament and Council of the European Union, 2025). Thus, the Directive focuses primarily on indicators used to diagnose and assess soil degradation rather than on a predefined classification of degradation processes or threats. However, based on the degradation processes addressed by the Directive and the recommendations of the EU Soil Observatory (EUSO), a broader list of ten major forms of soil degradation can be distinguished.

Main soil degradation process / threat	What it means?
1. Soil erosion	Removal of soil by **water, wind or other erosion processes**, resulting in loss of fertile topsoil and soil functions.
2. Loss of soil organic carbon (SOC)	Decline or insufficient level of organic carbon/organic matter, affecting fertility, structure, water retention and carbon storage.
3. Soil compaction	Increased soil density and reduced pore space, restricting root development, aeration, infiltration and biological activity.
4. Salinisation	Accumulation of soluble salts to concentrations that impair soil functions and plant growth.
5. Soil contamination	Presence of potentially harmful substances at levels that may adversely affect human health or the environment; includes both **local and diffuse contamination**.
6. Soil sealing	Permanent covering of soil by buildings, roads or other impermeable artificial surfaces, causing major or complete loss of natural soil functions.
7. Loss of soil biodiversity	Reduction in the diversity, abundance or functioning of soil organisms and biological processes.
8. Nutrient imbalance / excess nutrients	Nutrient levels outside an appropriate range, including excessive phosphorus/nitrogen or nutrient depletion, affecting soil and surrounding ecosystems.
9. Acidification	Excessively low soil pH affecting nutrient availability, biological processes and potentially increasing metal mobility.
10. Loss of soil water-retention capacity	Degradation of the soil's ability to absorb, store and supply water, increasing vulnerability to drought, runoff and flooding.

Table 1. Main soil degradation processes and threats identified by EU Soil Strategy

The EU Soil Strategy sets out the following key objectives to be achieved by 2050:

- Ensure that all EU soil ecosystems are healthy and more resilient, enabling them to continue providing essential ecosystem services.
- Achieve no net land take and reduce soil pollution to levels that are no longer considered harmful to human health or ecosystems.
- Make the protection and sustainable management of soils, as well as the restoration of degraded soils, common standards across the EU.

In view of these challenges, the policies and practical approaches adopted by local and regional administrations for managing degraded areas must also undergo fundamental changes. A crucial task is to reduce the extent of marginal land, particularly in peri-urban and rural areas, that has been degraded by historical industrial activities and the exploitation of natural resources or contaminated by industrial dust deposition, but is still classified as agricultural land in land-use and spatial planning documents. The restoration of such degraded ecosystems poses a major challenge for local authorities and landowners, as these areas have often lost their agricultural value and can no longer be safely used for food production. “Green”, nature-based adaptation measures should therefore focus on non-food agricultural uses, including the cultivation of more resilient industrial crops and tree species for biomass, energy, and other industrial purposes. It is important to develop realistic action plans and innovative solutions that support the sustainable management of marginal land while restoring its biological functions and productive potential. Future actions should safeguard soil ecosystem functions, enhance biodiversity, and protect these areas from conversion to built-up land and the associated soil sealing, which can contribute to the urban heat island effect. The proposed management solutions and development strategies may also provide alternative sources of income for local farmers in peri-urban areas and offer practical tools for adapting to continuing urban expansion and the resulting loss of agricultural land within and around cities. Presenting alternatives to conventional food production, combined with education and training for local farmers, can also contribute to the integration and active involvement of local communities through a participatory approach, while helping to prevent land-use conflicts. The development of universal procedures that can be routinely applied by local administrations to address the management and recovery of degraded land is therefore the main objective of this handbook, which represents the final output of the PoLaRecCE project.

Local and regional administrations and institutions responsible for soil management and spatial planning need affordable, simple, and reliable tools to obtain essential information on soil condition. Such information is necessary to develop appropriate land-use strategies and minimise health and ecological risks in urban, peri-urban, and rural areas used for agricultural activities. A frequent barrier to identifying and assessing soil quality in degraded areas is the high cost of chemical analyses required to determine contamination levels and assess fertilisation and

reclamation needs. The PoLaRecCE project has developed general procedures and guidelines for effective environmental site assessment based on innovative on-site measurement techniques and methodologies. In many cases, the management of degraded land is complex, and conventional solutions, such as allocating degraded areas for industrial development or converting them into commercial zones, are often applied. However, such land-use changes can adversely affect soil functions and biodiversity and may result in extensive soil sealing, thereby contributing to the urban heat island effect. Ongoing climate change also strongly affects soil quality, particularly through more frequent or severe droughts, which can increase susceptibility to soil erosion. Currently, one of the most common approaches to the reclamation of degraded urban and post-industrial areas is the establishment of green spaces for recreational purposes. In many rural and peri-urban areas, however, land affected by degradation or contamination continues to be used for agriculture, even where soil contamination may make it unsuitable for food production. This may significantly reduce the agricultural and economic value of the land, increase the extent of agricultural wasteland, and worsen the financial situation of local farmers. The solutions developed by an international team of experts within the PoLaRecCE project propose an alternative, environmentally friendly approach to the sustainable management and productive use of marginal land and agricultural wasteland. They aim to preserve or restore soil biological functions and productive potential through the implementation of non-food agricultural production strategies. Such an approach protects the soil environment, supports local farming communities, and may provide a basis for the development of renewable energy projects, such as biogas production. It can also support other industrial sectors that use biomass and other plant-derived raw materials.

Forms of land degradation defined by PoLaRecCE project

Many forms of soil degradation listed in the EU Soil Strategy are difficult to assess, as their evaluation requires specialized approaches, detailed investigations, and field measurements. Consequently, assessing these forms of degradation is often impractical for local and regional authorities. For example, assessing the extent of soil organic carbon (SOC) loss requires field sampling, costly laboratory analyses, and specialized soil science expertise to interpret the results. Similarly, assessing soil compaction requires specific field measurements and appropriate equipment. Soil biodiversity assessment relies on biological methods, which are often complex, time-consuming, and expensive. Assessing the loss of soil water retention capacity is equally challenging, as it requires information on soil physical properties, organic carbon content, and hydrological conditions. The lack of simple, desk-based assessment tools creates a "black box" for

municipal officials, making them heavily dependent on external scientific institutions and specialized expertise. Moreover, municipalities often lack sufficient financial resources to conduct comprehensive soil assessments across their territories. As a result, local and regional authorities often lack the capacity to conduct preliminary, large-scale assessments of soil degradation, identify priority areas requiring further investigation, and develop evidence-based land management strategies.

For this reason, within the framework of the PoLaRecCE project, we proposed 18 simplified categories of land degradation to be used in a survey designed to provide the basis for the development of a database of degraded areas. These categories were selected to facilitate the assessment of land degradation by local authorities, as identifying their occurrence and estimating their extent within a given municipality requires considerably less specialized knowledge. In some cases, the identification of these forms of degradation relies solely on local knowledge or information available in publicly accessible databases, without the need for specialized field investigations or laboratory analyses.

Chemical soil degradation – soil contamination caused by industrial and urban dust deposition

Description the problem and forms of land and soil degradation

This form of chemical soil degradation results from the atmospheric deposition of industrial and urban dust onto the soil surface and is generally classified as diffuse pollution. The process involves the deposition of airborne particulate matter emitted by mining and metallurgical industries, cement and ceramic production facilities, power plants, road transport, and domestic heating. Long-term atmospheric dust deposition leads to the gradual accumulation of potentially hazardous substances in the topsoil, particularly in the uppermost soil horizons (often within the top 10 cm), potentially causing substantial changes in soil chemical and biological properties. The most common potentially toxic elements (PTEs), depending on the pollution source, include lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni), and arsenic (As). Industrial and urban dust deposition may also introduce sulfur- and nitrogen-containing compounds into the soil, contributing to soil acidification and a reduction in its acid-buffering capacity. In addition, the accumulation of mineral particles, including silica and aluminosilicates, as well as soot and other carbonaceous particles, may modify the physical properties of the topsoil, particularly its texture, structure, and porosity.

In Central Europe, historical emissions from mining and metallurgical activities, including the extraction and processing of metal ores and other mineral resources, as well as the combustion of hard coal and lignite, which have been major energy sources in the region for centuries, have

played a particularly important role in soil contamination. Over the past century, road transport has also become a major source of soil pollution. In addition to exhaust emissions from diesel and gasoline engines, non-exhaust emissions originating from tire wear (a significant source of zinc), brake pad abrasion, and road surface wear contribute to soil contamination. The widespread introduction of catalytic converters, although substantially reducing emissions of harmful exhaust gases, particularly carbon monoxide and nitrogen oxides, has also introduced a new source of soil contamination by platinum-group elements (PGEs). These include primarily platinum (Pt), palladium (Pd), and rhodium (Rh), which can accumulate in urban soils and roadside areas exposed to heavy traffic. In many regions of Central Europe, where solid fuels are still widely used for domestic heating, emissions from low-level sources, commonly referred to as "low-stack emissions", also contribute significantly to local soil pollution.

The highest concentrations of PTEs associated with atmospheric deposition are generally found in the surface soil layers. Their mobility and vertical migration within the soil profile depend on soil properties, particularly pH, texture, organic matter content, and the presence of reactive mineral phases. Fine-textured soils rich in clay minerals and organic matter generally exhibit a greater capacity to retain metals.

In urban areas, the natural sequence of soil horizons is frequently disturbed by construction activities, soil excavation and redistribution, and the presence of technogenic materials or anthropogenic soil layers, including buried waste deposits beneath the surface horizon. These disturbances often complicate the assessment of soil contamination levels and the identification of pollution sources. Atmospherically deposited dust may become mixed with construction debris, anthropogenic fill materials, and soil organic matter, making it difficult to distinguish contamination originating from atmospheric deposition from that associated with other anthropogenic activities.

In areas with sparse or absent vegetation, as well as on paved surfaces such as roads and parking areas, deposited dust can undergo secondary resuspension and subsequent redeposition. Wind action and vehicle-induced turbulence can lift previously deposited particles back into the atmosphere, where they may be transported over short distances and subsequently deposited on nearby lawns, parks, and allotment gardens. This process contributes to the redistribution of potentially toxic elements within urban environments.

Soil contamination caused by industrial and urban dust deposition can have serious environmental and health consequences, posing direct and indirect risks to humans and other living organisms. Such PTEs as lead (Pb) and cadmium (Cd), can enter the human body through accidental ingestion of contaminated soil or dust, inhalation of airborne particles, or consumption of food crops grown in contaminated soils. Children playing on contaminated lawns and playgrounds are particularly vulnerable to exposure through incidental soil and dust ingestion. The cultivation of

edible crops, particularly vegetables consumed raw, may pose significant health risks where soil contamination exceeds safe levels. Therefore, food production should be restricted or excluded from contaminated areas where the concentrations and bioavailability of pollutants pose unacceptable risks to human health. Furthermore, chemical soil contamination may also contribute to biological soil degradation. Elevated concentrations of PTEs can adversely affect sensitive soil microorganisms and invertebrates, including earthworms, by disrupting physiological and metabolic processes, reducing their abundance and activity, and ultimately decreasing soil biodiversity. Soil pollutants may also enter food chains through uptake by plants and subsequent transfer to herbivores and predators, potentially leading to the accumulation of certain contaminants in living organisms. In addition, mobile forms of pollutants may migrate downward through the soil profile and eventually reach groundwater. Surface runoff and soil erosion can also transport contaminated soil particles and dissolved pollutants into nearby water bodies, contributing to the contamination of surface waters.

The scale of the problem in CE region

In Central Europe, soil contamination caused by industrial and urban dust deposition is largely a historical and is deeply rooted in the region's historical industrial development and economic structure. For more than a century, many parts of the region were major centres of European heavy industry, particularly coal mining, metallurgy, and chemical production. Although industrial dust emissions have declined substantially since the 1990s due to the introduction of modern emission control technologies and industrial restructuring, soils retain a long-term record of historical atmospheric pollution. Potentially toxic elements deposited decades ago remain accumulated in the topsoil, posing persistent environmental risks. This legacy contamination is further compounded by the ongoing atmospheric deposition of particulate matter, including PM10 and PM2.5, originating from road transport and low-stack emissions associated with the combustion of solid fuels, particularly coal and wood, in domestic heating systems.

In Central Europe, several historically industrialised regions have been particularly affected by soil contamination associated with industrial and urban emissions, including atmospheric dust deposition. The following areas represent important examples of industrial pollution hotspots:

- Upper Silesian Industrial Region and Dąbrowa Basin (Poland) – These areas have been affected by more than a century of intensive industrial activity, particularly coal mining, ferrous and non-ferrous metallurgy (including zinc and lead production), and coal-fired power generation. Historical atmospheric emissions have contributed to the widespread accumulation of PTEs in surface soils.
- Black Triangle (border region of Poland, the Czech Republic, and Germany) – This historical industrial region encompasses parts of Lower Silesia, northern Bohemia (including the Ústí

nad Labem and Teplice areas), and Saxony. During the second half of the 20th century, extensive lignite mining, lignite-fired power generation, and other industrial activities resulted in substantial atmospheric emissions of sulfur dioxide, particulate matter, and associated pollutants.

- Ostrava-Karviná Industrial Region (Czech Republic) – Located along the Polish border, this region has a long history of coal mining, coke production, iron and steel manufacturing, and other heavy industrial activities. It represents one of the major historical industrial pollution areas in the Czech Republic, with characteristics comparable to those of Upper Silesia.
- Central Slovakia (Slovakia) – Several industrial valleys have been affected by historical mining, energy production, and metallurgical activities. The Upper Nitra Basin, particularly around Prievidza and Nováky, was historically associated with lignite mining and coal-fired power generation. The Žiar nad Hronom area has been affected by aluminium production and associated emissions of fluoride-containing compounds and industrial dust.
- Northern Hungary (Miskolc and surrounding areas) – This region was historically an important centre of iron and steel production, coal mining, and heavy industry. Long-term industrial emissions have contributed to local soil contamination, particularly in the vicinity of former metallurgical facilities.
- Industrial and mining regions of Austria – Localised soil contamination associated with historical mining and metallurgical activities occurs in several areas, including Styria, particularly around Leoben-Donawitz, an important centre of iron and steel production. Another significant historical pollution hotspot is Arnoldstein in Carinthia, where centuries of lead and zinc mining and smelting resulted in the accumulation of potentially toxic elements in the surrounding environment. Other areas with historical mining and metallurgical activities include the Lavant Valley and the Hüttenberg region.
- Upper Meža Valley (Slovenia) – This region has been severely affected by centuries of lead and zinc mining and smelting. Historical atmospheric emissions and the weathering and erosion of mining and metallurgical wastes have contributed to substantial soil contamination, particularly with lead (Pb), zinc (Zn), and cadmium (Cd).
- Idrija region (Slovenia) – One of Europe's most important historical mercury mining centres, where several centuries of mercury extraction and ore processing have resulted in extensive environmental contamination with mercury (Hg), affecting soils, sediments, and surrounding ecosystems.
- Jesenice and Celje (Slovenia) – Both areas have a long history of industrial activity. Jesenice was an important centre of iron and steel production, while Celje was associated with zinc smelting and chemical manufacturing. Historical industrial emissions and waste disposal have contributed to the accumulation of PTEs in local soils.

- Spinetta Marengo (Piedmont, Italy) – A major industrial contamination hotspot associated with more than a century of chemical manufacturing near Alessandria. Historical industrial activities have resulted in soil and groundwater contamination involving various inorganic and organic pollutants, including chromium compounds, chlorinated solvents, and, more recently, per- and polyfluoroalkyl substances (PFAS).
- Lombardy (Italy) – Highly industrialised areas around Milan, Brescia, and Mantua have a long history of steel production, foundries, chemical manufacturing, and other industrial activities. These activities, together with urban and transport-related emissions, have contributed to localised soil contamination with potentially toxic elements, including lead (Pb), zinc (Zn), and nickel (Ni).
- Liguria (Italy) – Historical industrial activities, particularly shipbuilding, iron and steel production, coke processing, and mining, have contributed to soil contamination in several industrial and former mining areas. Historical mining and metallurgical waste deposits may also act as secondary sources of metal-rich dust, contributing to the redistribution of potentially toxic elements such as copper (Cu), iron (Fe), and other metals in the surrounding environment.

Sources of information to assess the problem on the local scale

Data on soil contamination with PTEs, including heavy metals and metalloids, are collected and made available in all Central European countries through various databases and monitoring systems. These data sources can generally be divided into two levels: pan-European and national. Pan-European databases are valuable tools for comparative assessments and for identifying regional patterns of soil contamination and geochemical background concentrations. Although these databases are generally publicly accessible and free of charge, their spatial resolution is often insufficient for detailed assessments at the municipal level. Nevertheless, they can provide preliminary indications of potential soil contamination problems within individual municipalities.

National databases and registers are particularly important for local and regional authorities, including municipalities, cities, and counties, as they may provide more detailed information on soil contamination, sometimes including site-specific measurements and monitoring results. In some countries, official registers also have a formal role in environmental management and regulatory procedures. Consequently, national data sources should serve as essential tools for supporting spatial planning, investment decisions, environmental risk assessment, and the identification of areas requiring further investigation or remediation.

Leakage of oil and petroleum products

Description the problem and forms of land and soil degradation

The leakage of crude oil and petroleum products causes soil degradation by altering its physical properties, chemical balance, and biological activity.

Physical degradation is primarily manifested by reduced soil aeration and oxygen availability. Oil coats soil particles and occupies pore spaces, restricting gas exchange and potentially creating anaerobic (oxygen-deficient) conditions. In addition, petroleum hydrocarbons can induce soil water repellency by forming hydrophobic coatings on soil particles. This reduces water infiltration and may increase surface runoff and soil erosion. Petroleum contamination can also alter the geotechnical properties of soil, potentially reducing its maximum dry density, shear strength, and overall stability while increasing compressibility.

Chemical degradation is associated with nutrient imbalances, particularly changes in the carbon-to-nitrogen (C/N) and carbon-to-phosphorus (C/P) ratios. The introduction of substantial amounts of petroleum-derived organic carbon can significantly increase these ratios, potentially leading to the immobilization of nitrogen and phosphorus by soil microorganisms. Consequently, the availability of essential plant nutrients, particularly nitrogen and phosphorus, may decrease. Petroleum contamination also introduces potentially toxic organic compounds, including volatile aromatic hydrocarbons such as benzene, toluene, ethylbenzene, and xylenes (BTEX), as well as polycyclic aromatic hydrocarbons (PAHs). Some of these compounds are persistent in soil, while others may migrate through the soil profile and contaminate groundwater.

Biological degradation is manifested by adverse effects on soil microorganisms, soil fauna, and vegetation. Toxic components of petroleum products can inhibit or reduce populations of beneficial soil bacteria, fungi, and earthworms, thereby disrupting essential biological processes, including organic matter decomposition and nutrient cycling. Plant growth may also be suppressed due to reduced oxygen availability, soil water repellency, nutrient imbalances, and the direct phytotoxic effects of petroleum hydrocarbons. These combined effects can impair water and nutrient uptake, resulting in stunted plant growth, reduced biomass production, and, in severe cases, complete vegetation loss.

Leaks of crude oil and petroleum products into the soil can come from many different sources, which are most often divided into industrial, transport and commercial-domestic as well as warfare and sabotage.

Industry and mining

- Oil extraction and production failures including leaks from oil wells, damage to wellheads, and failures of crude oil separation and processing systems during oil extraction and production.

- Storage tank leaks including corrosion, structural damage, or rupture of large aboveground and underground storage tanks at refineries, fuel depots, and oil terminals.
- Industrial and mining waste including improper storage, handling, or disposal of petroleum sludge, oil-contaminated industrial waste, and hydrocarbon-contaminated mine water.

Transportation and distribution

- Pipeline failures including ruptures and leaks in oil and petroleum product pipelines caused by corrosion, material defects, ground movements, or deliberate damage (e.g., including illegal tapping for fuel theft).
- Transportation accidents including road accidents involving fuel tankers, derailments of freight trains transporting petroleum products, and oil tanker accidents in coastal waters, potentially resulting in the contamination of beaches and coastal soils.
- Fuel handling and transfer operations including accidental spills during tanker loading and unloading, ship refuelling, and the transfer of petroleum products at railway terminals and distribution facilities.

Commercial, Service, and Residential Activities

- Fuel stations including leaks from underground storage tanks (USTs) containing gasoline or diesel fuel, as well as from associated pipelines connecting storage tanks to fuel dispensers. These facilities represent a potentially significant source of petroleum hydrocarbon contamination in urban areas.
- Vehicle repair workshops and scrapyards including improper storage, handling, or illegal disposal of used engine oils, hydraulic fluids, and transmission fluids, resulting in contamination of soil and potentially groundwater.
- Domestic heating systems including leaks from heating oil storage tanks, fuel supply lines, and oil-fired heating systems on residential properties or in small boiler facilities.

Warfare and sabotage

Damage to petroleum infrastructure including destruction or damage to oil refineries, fuel storage facilities, pipelines, and other petroleum infrastructure resulting from military operations, including bombing, shelling, and deliberate sabotage in areas affected by armed conflict.

The scale of the problem in CE region

In Central Europe, accidental leaks of crude oil and petroleum products still occur, but modern detection systems, stringent technical standards, and mandatory reporting and remediation procedures can significantly reduce their long-term environmental impact. Such incidents are also more likely to be detected and brought to the attention of the relevant authorities. Consequently, their locations should be known to local administrations, making it relatively easy to assess the

scale of the problem. A considerably greater, more complex, and more costly challenge is posed by historical soil contamination caused by leakage of crude oil and petroleum products. Legacy contamination sites sometimes referred to as "ecological time bombs", may remain undetected for decades, causing long-term soil degradation and groundwater contamination. In the former Eastern Bloc countries of Central Europe, such contamination is frequently associated with former military bases, abandoned refineries, and decommissioned heavy industrial facilities.

Sources of information to assess the problem on the local scale

Information on the locations of potential sources of leaks associated with fuel infrastructure within a municipality should be relatively easy to obtain. Reported failures and local incidents involving leaks of liquid fuels, crude oil, and petroleum products in recent years should also be documented in municipal records. Similarly, the locations of registered car repair workshops, petrol stations, and other facilities involved in the storage, handling, or distribution of petroleum products should be well known and documented.

Identifying historical sources of contamination presents a greater challenge. This is often complicated by incomplete historical records, unknown locations of underground infrastructure, and a lack of systematic environmental monitoring. Consequently, historical soil contamination by petroleum hydrocarbons remains a significant challenge for land-use planning, environmental risk assessment, and the redevelopment of degraded areas. Similar difficulties may arise when identifying illegal waste disposal and storage sites containing petroleum products. Nevertheless, a preliminary assessment of the scale of this problem within a municipality should be possible based on available documentation, historical land-use information, and records of reported environmental incidents.

Such information can help local administrations identify priority areas for further investigation, particularly former fuel storage facilities, petrol stations, industrial sites, and locations where accidental spills or illegal waste disposal may have occurred.

Leakage of oil and petroleum products

Description the problem and forms of land and soil degradation

Wastewater leakage and the uncontrolled disposal or application of sewage sludge can introduce a complex mixture of chemical and biological contaminants into the soil environment, adversely affecting its physical, chemical, and biological properties. Although properly treated sewage sludge (biosolids) can be used as a soil amendment to improve soil structure and provide essential plant nutrients, untreated wastewater leakage and the uncontrolled or excessive application of sewage sludge may cause severe soil degradation through several interrelated

processes, including chemical contamination and toxicity, biological degradation and microbial imbalances, deterioration of soil physical properties, and secondary environmental impacts.

Chemical contamination and toxicity

- Wastewater and sewage sludge may contain elevated concentrations of PTEs, including lead, cadmium, copper, zinc, and nickel. Unlike organic contaminants, these elements are not subject to biodegradation and may accumulate in the topsoil following repeated sludge application or prolonged wastewater contamination.
- Wastewater and sewage sludge may contain a wide range of organic contaminants, including persistent organic pollutants (POPs), per- and polyfluoroalkyl substances (PFAS), brominated flame retardants, pharmaceuticals, and microplastics. Some of these substances are highly resistant to environmental degradation and may accumulate in soils following repeated sludge application.
- Wastewater, particularly from industrial or certain municipal sources, may contain elevated concentrations of dissolved salts. Repeated wastewater infiltration or irrigation, especially under conditions of high evaporation and insufficient drainage, can lead to salt accumulation in the soil profile.

Biological degradation and microbial imbalance

- Untreated wastewater and sewage sludge may contain pathogenic microorganisms, including bacteria such as *Escherichia coli* and *Salmonella*, as well as viruses, protozoa, and parasitic helminths. Some of these organisms can survive in soil for extended periods, depending on environmental conditions. Their presence may pose risks to human and animal health, particularly through direct contact, contaminated crops, or the transfer of pathogens to surface water and groundwater.
- The presence of potentially toxic elements (PTEs), organic contaminants, microplastics, and other pollutants introduced into soil through wastewater or sewage sludge may adversely affect soil organisms, including earthworms, mycorrhizal fungi, and native microbial communities. Depending on contaminant concentrations and exposure conditions, these substances can alter microbial community composition, reduce the abundance or activity of sensitive organisms, and disrupt essential biological processes, including organic matter decomposition, nutrient cycling, and soil aggregation.

Physical degradation of soil structure

- Suspended solids, organic particles, fats, and oils present in wastewater may accumulate within soil pores, reducing hydraulic conductivity and limiting water infiltration. Under conditions of prolonged saturation or excessive organic loading, oxygen consumption by microorganisms may exceed oxygen replenishment, leading to oxygen-deficient or anaerobic conditions. These conditions can inhibit root respiration, alter microbial processes, and promote the formation of reduced compounds and gases responsible for unpleasant odours.

- Excessive wastewater application or inappropriate sewage sludge management may adversely affect soil structure through changes in aggregate stability, pore distribution, and hydraulic properties. In particular, high sodium concentrations may promote clay dispersion and reduce soil permeability. Where these processes lead to surface sealing, reduced vegetation cover, or the deterioration of soil aggregation, susceptibility to surface runoff and water erosion may increase.

Secondary environmental impacts

- Wastewater and sewage sludge may introduce substantial amounts of nitrogen and phosphorus into soils. When nutrient inputs exceed plant uptake and the soil's capacity to retain these elements, surplus nutrients may be transported beyond the root zone or into adjacent water bodies. Nitrate is particularly susceptible to leaching and may contaminate groundwater, whereas phosphorus is generally transported through surface runoff, soil erosion, or preferential flow pathways, although leaching may also occur under certain soil conditions. Excessive nutrient inputs to surface waters can contribute to eutrophication, algal blooms, oxygen depletion, and the deterioration of aquatic ecosystems.

The main sources of wastewater leakage and uncontrolled sewage sludge disposal or application that may contribute to soil degradation can be classified into four major categories: municipal infrastructure, industrial activities, agricultural practices, and inadequate waste management.

Municipal infrastructure and urban runoff

- Corroded, cracked, or poorly maintained underground sewer pipes may release untreated municipal wastewater into the surrounding soil and subsoil, potentially causing chemical and biological contamination.
- During heavy rainfall, combined sewer systems carrying both municipal wastewater and stormwater may exceed their hydraulic capacity, resulting in the discharge of untreated or partially treated sewage mixed with stormwater onto surrounding land or into nearby water bodies.
- Damaged, malfunctioning, or poorly maintained septic tanks and associated drainage systems may release insufficiently treated domestic wastewater into surrounding soils, potentially contaminating both soil and groundwater.

Generally, municipal and domestic wastewater sources may contribute to the accumulation of pathogens, pharmaceuticals, microplastics, and household chemicals in soils, potentially leading to disruptions in soil biological processes, pore clogging, and the development of anaerobic conditions.

Industrial operations and discharges

- Industrial facilities, particularly those involved in textile manufacturing, chemical production, electronics, and leather tanning, may generate wastewater containing elevated concentrations of PTEs, synthetic dyes, solvents, and other hazardous substances.

Accidental releases, inadequate treatment, or illegal discharges may lead to contamination of surrounding soils.

- Mining and mineral processing activities may generate substantial quantities of contaminated wastewater and sludge, potentially containing elevated concentrations of dissolved metals, metalloids, and other inorganic contaminants. Acid mine drainage, where present, may cause soil acidification and increase the mobility and bioavailability of PTEs.
- Refineries, petrochemical plants, and fuel storage facilities may release oily wastewater and petroleum hydrocarbons through accidental spills, leaks, or inadequate wastewater management.

Generally, wastewater from industrial and mining activities may introduce heavy metals (mostly lead, cadmium) as well as solvents, acids, and hydrocarbons into soils, potentially causing severe chemical contamination, soil toxicity, and long-term deterioration of soil fertility.

Mismanaged agricultural activities

- The application of insufficiently treated sewage sludge or excessive quantities of sludge to agricultural land may introduce PTEs, organic contaminants, microplastics, and pathogenic microorganisms into the soil. Repeated application may result in the accumulation of persistent contaminants and adversely affect soil quality and biological functions.
- Large livestock farms generate substantial quantities of liquid manure and slurry. Leakage from storage facilities, improper disposal, or excessive application to agricultural land may lead to nutrient accumulation, increased nitrate leaching, microbial contamination, and, under certain conditions, soil salinization.
- In regions experiencing water scarcity, untreated or inadequately treated municipal wastewater may be used for agricultural irrigation. Repeated application can introduce salts, PTEs, organic contaminants, and pathogens into agricultural soils, potentially leading to their accumulation and long-term soil degradation.

Generally, wastewater from agricultural and livestock farming activities may introduce excessive amounts of nitrogen, phosphorus, salts, and antibiotic residues into soils, potentially leading to nutrient overloading, soil salinization, and adverse effects on plant growth.

Inadequate waste management systems

- Wastewater storage and settling ponds associated with municipal treatment plants or industrial facilities may allow contaminated water to infiltrate the underlying soil if they lack adequate impermeable barriers or are improperly maintained. Such leakage may result in long-term soil and groundwater contamination.
- Uncontrolled disposal of septic tank waste, untreated sewage sludge, or industrial sludge on abandoned land, agricultural fields, or forested areas may introduce hazardous substances and pathogens into the soil, adversely affecting soil quality, biological activity, and ecosystem functions.

Generally, wastewater from inadequately managed wastewater treatment plants and waste management facilities may introduce heavy metals and other PTEs, PFAS as well as other organic pollutants into soils, potentially leading to their accumulation, transfer through soil food webs, and long-term toxic effects on soil organisms.

The scale of the problem in CE region

The problem of soil degradation associated with wastewater and sewage sludge in Central Europe is closely related to differences in national regulations and sludge management practices, as well as intensive agricultural and industrial activities.

Countries in the region apply different approaches to sewage sludge management, which influence the nature and extent of potential soil degradation. In Germany and Austria, sewage sludge incineration is an important management option, particularly as regulations increasingly restrict its direct agricultural application. Incineration reduces the risk of introducing pathogens and organic contaminants into agricultural soils through sludge application. However, it also generates ash containing concentrated inorganic constituents, including PTEs. The disposal or further treatment of this ash requires appropriate environmental safeguards to prevent secondary contamination.

In Poland, the Czech Republic, Slovakia, and Hungary, agricultural application remains one of the sewage sludge management options, although its importance varies considerably between countries. When properly treated and applied in accordance with environmental regulations, sewage sludge can provide organic matter and nutrients that improve soil fertility. However, repeated or poorly controlled application may contribute to the accumulation of potentially toxic elements and persistent organic pollutants in the topsoil. In regions with a long history of industrial activity, such as Silesia in Poland and mining and metallurgical regions in the Czech Republic and Slovakia, particular attention should be paid to the possible presence of cadmium, lead, mercury, and other potentially toxic elements in sewage sludge.

In recent years, microplastics contained in sewage sludge have emerged as an additional environmental concern in Central Europe. These contaminants, including synthetic fibres and plastic fragments, may accumulate in agricultural soils following repeated sludge application. Depending on their concentration, size, and composition, microplastics can affect soil structure, water retention, microbial activity, and soil organisms. However, the extent and direction of these effects depend on soil properties and environmental conditions.

Other emerging contaminants of concern include per- and polyfluoroalkyl substances (PFAS), often referred to as "forever chemicals", as well as pharmaceutical residues, including antibiotics and hormones. PFAS are a large group of persistent synthetic chemicals used in various industrial and consumer products, whereas pharmaceutical residues originate mainly from human and

veterinary medicine. Many of these substances are not completely removed by conventional wastewater treatment processes and may enter agricultural soils through sewage sludge application. PFAS can accumulate in soils and, depending on the compound, may be taken up by plants or transported into groundwater. Pharmaceutical residues, particularly antibiotics, may affect soil microbial communities and contribute to the selection of antibiotic-resistant bacteria. Some of these contaminants may also cause phytotoxic effects at sufficiently high concentrations.

Sources of information to assess the problem on the local scale

For local administrations, these risks highlight the importance of obtaining information on sewage sludge treatment and disposal practices, monitoring its agricultural application, and identifying areas where long-term sludge use may have contributed to soil contamination. Particular attention should be paid to agricultural land receiving repeated sludge applications and to areas located near wastewater treatment plants and sludge storage facilities.

To effectively assess the extent of soil degradation associated with sewage sludge and wastewater, local administrations should combine existing administrative records with GIS-based spatial analyses and, where necessary, targeted field investigations. Since sewage sludge and wastewater may introduce a wide range of chemical and biological contaminants into the environment, information from several complementary sources is needed to identify potentially affected areas and assess the associated risks.

Existing administrative records and databases

Administrative records and national databases are essential sources of information, as they can provide data on the production, treatment, transport, and agricultural application of sewage sludge. In countries where the agricultural use of sewage sludge is permitted, wastewater treatment plants and other responsible entities are generally required to maintain records of sludge quantities, quality, and disposal or recovery methods, in accordance with national regulations. Depending on the country and reporting system, these records may also contain information on the locations and cadastral identification of agricultural plots where sewage sludge has been applied.

Additional information may be obtained from laboratory test reports maintained by wastewater treatment plants, cadastral maps, environmental permits, and administrative decisions concerning the agricultural use of sewage sludge. Laboratory analyses typically include selected chemical and microbiological parameters, such as pH, potentially toxic elements, and indicators of pathogen contamination, although the exact requirements vary between countries.

National waste management databases, can provide useful information on sewage sludge generation and management. Where historical application records are available, local administrations may use them to identify agricultural plots that have received repeated sludge applications over the past 10–20 years. Such areas should be considered potential priority sites for

further investigation rather than confirmed contamination hotspots.

Remote sensing and GIS-based spatial analyses

Remote sensing and GIS tools can complement administrative records by providing spatial information on land use, wastewater infrastructure, and areas potentially affected by sewage-related pollution. Freely available satellite imagery, including data from the Copernicus programme, as well as commercial high-resolution imagery, can help identify land-use changes, wastewater treatment facilities, sludge storage areas, and flood-prone zones.

However, satellite imagery generally cannot directly detect historical sewage leaks, illegal wastewater discharges, or chemical contamination of soils. Identifying such problems requires additional information from infrastructure maintenance records, environmental inspections, incident reports, and, where necessary, field investigations.

By combining administrative records, historical information, GIS analyses, and targeted soil testing, local administrations can identify potentially affected areas, prioritize sites requiring further investigation, and make a preliminary assessment of the extent of soil degradation within their municipalities.

Contamination by volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs)

Description the problem and forms of land and soil degradation

Volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), particularly those originating from anthropogenic sources such as urban and industrial activities, waste disposal, and agricultural practices, can significantly affect soil quality and ecosystem functions. Depending on their physicochemical properties, these contaminants may migrate through the soil profile or accumulate in particular soil horizons, potentially causing chemical contamination and biological degradation. Their presence may alter soil microbial communities, inhibit essential biological processes, and adversely affect plant growth. Although soils act as important environmental sinks for many organic pollutants, excessive contamination may overwhelm their natural attenuation capacity, resulting in long-term deterioration of soil quality and ecosystem functions. These contaminants may enter the soil through accidental fuel leaks, industrial spills, improper waste disposal, and atmospheric deposition, particularly of particle-bound PAHs originating from industrial processes, vehicle emissions, and residential fuel combustion ("low-stack emissions").

The presence of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) in soils may contribute to soil degradation through three main mechanisms:

Phytotoxicity and reduced vegetation establishment

- Elevated concentrations of certain VOCs and PAHs may inhibit plant growth and reduce the capacity of contaminated soils to support vegetation.
- Some organic contaminants may damage plant roots, inhibit physiological processes, and reduce water and nutrient uptake. At sufficiently high concentrations, these effects may result in reduced plant growth, vegetation decline, or plant mortality.
- Contamination by VOCs and PAHs may inhibit seed germination, root development, and plant establishment, creating additional challenges for the restoration of degraded land and the development of lawns, parks, and other urban green spaces.

Disruption of soil microbial communities and ecosystem functions

- Soil microorganisms play an essential role in organic matter decomposition, nutrient cycling, and the maintenance of soil ecosystem functions. Exposure to elevated concentrations of certain VOCs and PAHs may adversely affect these processes.
- Organic contaminants may inhibit the activity of sensitive bacteria and fungi, reduce microbial diversity, and alter the composition and functioning of soil microbial communities. However, some microorganisms can tolerate or biodegrade specific organic pollutants.
- Reduced biological functioning and natural attenuation capacity: Changes in microbial activity may disrupt organic matter decomposition and nitrogen and phosphorus cycling. Severe contamination may also reduce the soil's capacity for natural biodegradation and recovery, potentially contributing to long-term deterioration of soil quality.

Long-term pollutant persistence, migration, and secondary emissions

- Contaminated soils may act as long-term reservoirs of organic pollutants and, under certain environmental conditions, become secondary sources of contamination affecting the atmosphere, groundwater, and terrestrial ecosystems.
- Secondary emissions of VOCs: Depending on their volatility, concentration, and soil conditions, VOCs may migrate through soil pores and be released into the atmosphere. Such emissions may contribute to local air pollution and, in some cases, create exposure risks through soil vapour intrusion into buildings.
- Long-term persistence of PAHs: Many PAHs, particularly high-molecular-weight compounds such as benzo[a]pyrene, exhibit low water solubility and strong sorption to soil organic matter. Consequently, they may persist in contaminated soils for extended periods, sometimes decades. Certain PAHs are carcinogenic or mutagenic and may pose long-term ecological and human health risks, depending on their bioavailability and exposure pathways.

The main sources of VOC contamination in urban soils include petroleum products, organic solvents, and industrial chemicals released at former industrial facilities, old landfills, and illegal waste disposal sites. These substances may migrate into groundwater or volatilize and enter nearby

buildings through soil vapour intrusion. Consequently, sites designated for redevelopment where VOC contamination is suspected or confirmed may require soil gas investigations and site-specific risk assessments before construction.

PAHs in urban soils originate mainly from incomplete combustion of coal, wood, and other fuels, industrial emissions, road traffic, and historical use of coal tar-based materials. Many PAHs are persistent and can accumulate in soils over long periods. Elevated concentrations may restrict agricultural, residential, or recreational land use and require appropriate remediation or risk-management measures. Depending on contamination levels and site conditions, these may include soil excavation, treatment, or containment.

The scale of the problem in CE region

In contrast to Southern Europe, where the main land degradation problems are water erosion and desertification, Central Europe faces severe chemical soil degradation resulting from a dense network of historical and active industrial areas. Approximately 16–20% of contaminated sites are reportedly affected by organic pollutants, including polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs), such as benzene, toluene, ethylbenzene, xylene, and other volatile compounds (Panagos et al., 2013). A significant proportion of these contaminated sites is located within the major industrial regions of Central Europe Independent scientific studies conducted in urban and forest soils across Central Europe, particularly in the belt extending from the Czech Republic through southern Poland to Hungary, have revealed alarmingly high local concentrations of these pollutants (Łyszczarz et al., 2024; Rykała et al., 2026). These elevated concentrations are usually found in local contamination hotspots associated with urban agglomerations and post-industrial areas, particularly in the vicinity of active and former coking plants (Rachwał et al., 2015; Ilić et al., 2020). In Central Europe, important sources of soil contamination by PAHs include emissions from domestic heating with coal and biomass, particularly from outdated heating systems (so-called low-stack emissions), as well as road transport. Studies conducted in densely populated urban areas have also indicated seasonal variations in PAH concentrations, with higher levels of atmospheric deposition during the autumn and winter heating season, potentially contributing to the accumulation of these pollutants in urban soils (Rusănescu et al., 2024; Rykała et al., 2026).

Sources of information to assess the problem on the local scale

For local administrations in individual Central European (CE) countries, assessing the extent of soil contamination by VOCs and PAHs is a challenge because these pollutants are generally invisible and their detection requires specialized analyses.

Local administrations can use information available from freely accessible European databases, such as the European Soil Data Centre (ESDAC) and the Land Use/Cover Area Frame Survey (LUCAS), as well as more detailed information from national registers. Although European databases generally do not provide sufficiently detailed spatial information for assessing contamination at the level of individual land plots, they can be useful for preliminary screening and identifying areas potentially at risk. Regional-scale data may help determine whether a municipality is located within an area characterized by elevated concentrations of certain soil contaminants. However, such data cannot identify whether a specific plot previously occupied by a petrol station or industrial facility is contaminated with VOCs or PAHs.

Other useful sources of information include the European Pollutant Release and Transfer Register (E-PRTR) and the Copernicus Land Monitoring Service (CLMS). The E-PRTR provides publicly accessible information on reported emissions of various pollutants, including certain PAHs and VOCs, from large industrial facilities. It allows local administrations to identify industrial plants within or near their municipalities that have reported emissions of these compounds. However, reported emissions do not necessarily indicate soil contamination at a particular site and also not include historical pollution.

The CLMS provides freely accessible land-cover and land-use data, including detailed spatial information for urban areas through products such as the Urban Atlas. These data can help identify industrial areas, transport infrastructure, and other land uses potentially associated with soil contamination. When combined with historical land-use information, they may also help locate former industrial sites (brownfields) and other potentially contaminated areas.

Additional information can be obtained from municipal documentation, including land and building registers, historical land-use records, and local environmental reports. For example, plots classified as industrial areas or transport areas may indicate locations where further investigation of possible VOCs and PAHs contamination is justified. However, these land-use categories should be treated as preliminary indicators rather than direct evidence of contamination.

By combining information from European databases, national registers, land-use records, and local environmental documentation, local administrations can identify potentially contaminated areas and make a preliminary assessment of the scale of the problem within their municipalities. More detailed site investigations and chemical analyses are necessary to confirm contamination and assess the associated environmental and health risks.

Chemical degradation by cyanides

Description the problem and forms of land and soil degradation

Cyanides are a group of chemical compounds containing a cyano group, consisting of one

carbon atom and one nitrogen atom. These are highly toxic substances that, at higher concentrations, can pose a lethal threat to humans and animals because they block cellular respiration. Therefore they high concentration in soil degrade mostly their biological functions but also negatively influence the chemical and physical properties. Cyanides are highly toxic substances that act as metabolic poisons. Once absorbed into the body, cyanide binds to the iron centre of cytochrome c oxidase, an enzyme located in the mitochondria, thereby inhibiting cellular respiration. As a result, cells are unable to utilise oxygen effectively, even when sufficient oxygen is available in the blood. This leads to rapid cellular hypoxia, primarily affecting organs with high oxygen demands, particularly the brain and heart.

Cyanide and cyanogenic compounds occur naturally in the environment and may be present in soils at low concentrations as part of natural biogeochemical processes. Cyanogenic glycosides are found in various plants, including the seeds of certain fruits (e.g., apricots, peaches, and cherries), bitter almonds, bamboo shoots, and cassava. During the decomposition of plant residues containing cyanogenic glycosides, hydrogen cyanide (HCN) may be released into the surrounding soil. Certain plants and microorganisms, including some fungi and bacteria, can also produce cyanide, which may be released into the rhizosphere and contribute to interactions with other organisms, including plant pathogens. At low concentrations, naturally occurring cyanide is generally subject to microbial transformation and degradation, limiting its persistence and potential toxicity in soil. Some soil microorganisms can utilise cyanide as a nitrogen source, converting it into less toxic compounds through specific enzymatic pathways.

Another important source of hydrogen cyanide (HCN) emissions into the atmosphere is biomass burning, including forest fires, as well as building fires, particularly those involving nitrogen-containing synthetic materials. During combustion, these materials can release substantial amounts of HCN into the atmosphere. Atmospheric HCN may subsequently be transported over considerable distances and partially removed through wet deposition or uptake by soil and vegetation. However, due to its relatively high volatility, HCN generally has a limited tendency to accumulate in dry surface soils. Its environmental behaviour depends strongly on soil pH, moisture content, temperature, and microbial activity. In the atmosphere, HCN is relatively persistent and is removed primarily through reactions with hydroxyl radicals and uptake by the oceans, rather than through rapid direct photodegradation. Although forest and industrial fires occur in Central Europe, soil contamination resulting from atmospheric HCN emissions is generally expected to be limited and temporary. The relatively high volatility of HCN, together with atmospheric dispersion and its potential for microbial degradation in soil, reduces the likelihood of its long-term accumulation. Consequently, fire-related HCN emissions are unlikely to cause persistent soil contamination or long-term impairment of soil biological functions under typical environmental conditions.

However, industrial activities represent a major anthropogenic source of cyanide

contamination in soils, potentially resulting in the accumulation of toxic cyanide compounds when their release exceeds the natural attenuation capacity of soil ecosystems. Industrial contamination poses a particularly serious environmental threat because cyanide-containing wastes and industrial effluents can introduce substantial amounts of these toxic compounds directly into the soil, resulting in high local concentrations and potentially long-term contamination. Despite their toxicity, cyanide compounds are widely used in various industrial processes. Sodium cyanide is extensively employed in gold and silver mining to extract these metals from their ores. Cyanide compounds are also used in electroplating, chemical manufacturing, and the production of certain plastics and pesticides. Among the major historical sources of cyanide contamination in soils are the coking industry and manufactured gas production, where cyanide compounds are generated as by-products of coal processing and may be released into the environment through industrial wastewater, waste disposal, and accidental leakage.

One of the major industrial sources of cyanide contamination is gold and silver mining, where sodium cyanide is widely used to extract precious metals from ores through cyanide leaching. Accidental spills, leaks, and failures of tailings storage facilities can release substantial amounts of cyanide-containing solutions into the surrounding environment, potentially causing severe soil and groundwater contamination. Other important sources include metal finishing and electroplating industries, where cyanide-containing compounds are used in certain technological processes and may be released through improperly managed industrial wastewater and waste disposal. A less widely recognised source of cyanide compounds in roadside soils is the use of ferrocyanide-based anti-caking agents, such as sodium or potassium ferrocyanide, in some road de-icing salts. These compounds may be transported into roadside soils by runoff and infiltration, although their environmental behaviour and toxicity differ considerably from those of free cyanide.

In extreme cases, high concentrations of bioavailable cyanide can severely inhibit soil microbial activity, potentially causing substantial reductions in microbial populations and plant death due to the inhibition of cellular respiration. Furthermore, free cyanide and certain soluble cyanide complexes can exhibit high mobility in soils due to their limited sorption onto soil particles, allowing them to migrate through the soil profile and potentially contaminate groundwater.

The scale of the problem in CE region

In Central Europe, major historical sources of cyanide contamination in soils include former industrial sites (so-called legacy sites), particularly those associated with coal gasification and coke production. Among the most important sources are former manufactured gas plants and coking facilities. During the 19th and 20th centuries, numerous plants producing town gas from coal operated throughout the region. Hydrogen cyanide (HCN) was generated as a by-product of the

high-temperature processing of coal and was subsequently removed from the gas during purification. Spent gas purification materials, often containing substantial amounts of iron-cyanide compounds, were frequently disposed of or stored directly on the ground near these facilities. Cyanide reacted with iron to form relatively stable complexes, including Prussian blue (ferric ferrocyanide). Although these compounds are generally less toxic and less mobile than free cyanide, some iron-cyanide complexes can undergo photodecomposition when exposed to sunlight or release cyanide under certain chemical conditions. Consequently, contaminated soils at former gasworks and coking plants may remain a potential source of cyanide contamination for decades, particularly where changes in environmental conditions promote the mobilisation or transformation of cyanide compounds.

Central Europe also has a high concentration of traditional metalworking, automotive, and machinery manufacturing industries, particularly in industrial regions of Poland, the Czech Republic, and eastern Germany. Cyanide compounds, primarily sodium and potassium cyanide, have historically been widely used in certain electroplating processes, while cyanide-based salt baths have also been employed in steel surface hardening. Improper management and disposal of cyanide-containing industrial wastewater and wastes have contributed to the contamination of numerous former industrial sites, some of which remain environmental hotspots. At these sites, cyanide may occur in various chemical forms, including free cyanide and metal-cyanide complexes, posing potential risks to soil ecosystems and groundwater.

Another specific and often overlooked potential source of cyanide compounds in Central European soils is the use of ferrocyanide-based anti-caking agents in road de-icing salts. Sodium or potassium ferrocyanide may be added to road salt (sodium chloride) to prevent caking during storage and handling. Improper storage of treated road salt, as well as runoff from treated roads, can introduce ferrocyanide compounds into surrounding soils and drainage systems. Although these compounds are generally much less toxic than free cyanide, their environmental behaviour depends on local conditions, including exposure to sunlight, soil pH, and the mobility of dissolved iron-cyanide complexes.

Sources of information to assess the problem on the local scale

Local and regional administration can obtain information on potential cyanide contamination in soils from national and regional contaminated land registers, environmental monitoring databases, historical industrial records, and previous environmental investigations. Particular attention should be paid to former gasworks, coking plants, electroplating facilities, and industrial waste disposal sites, where cyanide compounds may persist in soils for decades. Historical land-use maps and industrial archives can help identify potentially contaminated sites that have

not yet been included in official registers.

Where existing information is insufficient, local authorities should undertake preliminary site assessments followed by targeted soil and, where necessary, groundwater sampling. Chemical analyses should distinguish between free cyanide and more stable metal-cyanide complexes, as their toxicity, mobility, and environmental persistence differ considerably.

The collected information can support spatial planning, brownfield redevelopment, environmental risk assessment, groundwater protection, and the prioritisation of remediation activities. In particular, identifying cyanide-contaminated sites before allocating land for residential, recreational, or agricultural purposes can help prevent potential risks to human health and soil ecosystems.

Dumping of wastes materials from coal mining

Description the problem and forms of land and soil degradation

Coal mining waste disposal sites mainly contain waste rock, overburden (particularly from open-pit mines), and waste materials generated during coal processing. The accumulation of large amounts of mining waste causes significant land and soil degradation. Apart from occupying large areas of land, these waste deposits can trigger physical, chemical, and biological processes that change soil properties and damage the surrounding environment. Their effects may extend beyond the disposal sites, affecting nearby agricultural land, water resources, and residential areas.

The main ways in which coal mining waste contributes to soil and land degradation include:

Physical damage and land loss

Burial and loss of fertile soil: Large amounts of mining waste deposited directly on the ground cover or destroy the original fertile topsoil. Where natural topsoil is no longer available, mining waste may be used as a growing medium during land reclamation. However, such material usually has poor structure, low nutrient content, and limited ability to support plant growth. Over time, new technogenic soils may develop on these artificial deposits.

Soil compaction: Heavy machinery used to transport and deposit mining waste compresses the soil, reducing the spaces between soil particles. As a result, water infiltration, air circulation, and root development become more difficult.

Soil erosion and slope instability: Mining waste heaps often have steep slopes and little or no vegetation. Heavy rainfall can wash away loose material, causing soil erosion, slope failures, and the accumulation of sediments in nearby streams, drainage systems, and agricultural areas.

Chemical contamination and toxicity

Acid mine drainage: Mining waste may contain minerals such as pyrite, which react with oxygen and water and can produce acidic drainage. This acidic water can lower soil pH, increase

the mobility of harmful substances, and negatively affect soil fertility and plant growth.

Leaching of potentially toxic elements: Water passing through mining waste may carry potentially toxic elements, including arsenic, cadmium, lead, zinc, and chromium, into surrounding soils, surface waters, and groundwater. Such contamination can remain in the environment for many years and may restrict the safe use of affected land.

Soil salinity: Some mining wastes contain high amounts of soluble salts that can gradually accumulate in surrounding soils. High salt concentrations make it difficult for plants to absorb water and can reduce soil fertility and agricultural productivity.

Biological and ecological degradation

Loss of soil biodiversity: Unfavourable soil conditions, including high concentrations of harmful substances, excessive acidity, and limited water availability, can reduce the activity and diversity of soil microorganisms. This negatively affects the natural processes responsible for nutrient cycling and maintaining soil fertility.

Loss of vegetation cover: Mining waste often provides poor conditions for plant growth because of limited nutrients, contamination, and unfavourable physical properties. These conditions can slow down the natural development of vegetation and delay the recovery of degraded land. However, some abandoned mining waste heaps may gradually become covered by vegetation through natural succession.

Thermal degradation caused by spontaneous combustion

Spontaneous combustion of mining waste: Waste heaps containing residual coal may undergo spontaneous heating and combustion. Underground fires can continue for many years, generating high temperatures that destroy soil organic matter and change the chemical and mineral properties of the waste material. These fires may also release harmful gases and dust into the atmosphere, creating additional environmental and health risks for nearby communities.

The scale of the problem in CE region

In Central Europe, coal mining waste disposal sites are concentrated mainly in traditional coal mining regions. The most affected areas include:

Upper Silesian Coal Basin (Poland): This region has one of the largest concentrations of coal mining waste heaps in Central Europe. According to available estimates, mining waste disposal sites occupy approximately 10,000 hectares of land, much of which has been excluded from agricultural and forestry use.

Ostrava-Karviná Coal Basin (Czech Republic): The situation is similar to that in Upper Silesia. Large amounts of mining waste have accumulated within a relatively small and densely populated area, creating additional pressure on land availability, urban development, and spatial planning.

In other parts of Central Europe (Austria, Hungary, eastern Germany, and Slovakia), underground coal mining was carried out on a smaller scale and largely ceased during the 20th century or in the early 21st century. Nevertheless, former mining waste heaps may still pose environmental problems in some municipalities.

The situation is different in regions where lignite (brown coal) is extracted by open-pit mining. The main environmental problem is not the accumulation of waste rock heaps but the removal and displacement of enormous quantities of overburden, including soil, sand, and clay, to expose coal seams. These activities cause extensive changes to the landscape, destroy natural soil profiles, and significantly alter local and regional water conditions.

The main lignite mining regions in Central Europe include Lusatia and the Central German lignite mining district (Germany), Bełchatów, Konin, and Turów (Poland), the North Bohemian Basin (Czech Republic), and several historical mining areas in Hungary and Slovakia.

Open-pit mining involves the removal of soil and underlying geological materials across extensive areas, sometimes covering tens of square kilometres. The removed material is deposited in external waste dumps or used to fill previously excavated areas. As a result, natural soil profiles are destroyed, large areas of land are transformed, and their original agricultural, forestry, or ecological functions may be lost for many years. Reclamation and the development of new soils are therefore essential for restoring these areas to productive or other beneficial uses.

Sources of information to assess the problem on the local scale

Local authorities should have little difficulty identifying mining waste disposal sites within their municipality and assessing the scale of this form of land degradation. Above-ground waste heaps are usually clearly visible in the landscape. Their locations are also generally well documented, even in the case of historical waste disposal sites established more than 100 years ago. However, assessing their environmental impact, particularly the potential contamination of surrounding soils and water resources, may require additional investigations. Coal mining waste disposal sites can create long-term environmental problems that extend beyond their boundaries. Local authorities should consider these areas when preparing land-use plans, assessing environmental risks, and planning land reclamation activities. Particular attention should be paid to the potential contamination of surrounding agricultural soils, surface waters, and groundwater, as well as to the stability of waste heaps and the risk of spontaneous combustion. Regular environmental monitoring and appropriate land management can help reduce these risks and support the safe reuse of degraded land.

Dumping of wastes materials from ore mining

Description the problem and forms of land and soil degradation

The disposal of waste materials from ore mining causes land and soil degradation through chemical contamination, physical damage, and disruption of natural ecosystems. When mining waste, such as tailings, waste rock, and overburden, is deposited on the ground, it can significantly change soil properties and negatively affect the surrounding environment. These impacts may persist for many years and extend beyond the waste disposal sites.

The main mechanisms through which ore mining waste contributes to land and soil degradation include:

Chemical contamination and acidification

Acid mine drainage (AMD): Many metal ores contain sulfide minerals, such as pyrite. When exposed to air and water, these minerals can oxidise and produce acidic drainage. This acidic water may enter surrounding soils and water resources, lowering soil pH and increasing the mobility of harmful substances.

Contamination with potentially toxic elements: Mining waste may contain potentially toxic elements, including arsenic, lead, cadmium, mercury, and copper. Under acidic conditions, many of these elements become more mobile and can spread into surrounding soils, surface waters, and groundwater. High concentrations of these substances may negatively affect soil microorganisms, reduce soil fertility, and limit plant growth.

Physical damage and land transformation

Loss of fertile topsoil: Mining waste is often deposited directly on the ground, covering the original fertile topsoil. As a result, the natural soil profile is buried, and its biological functions are severely reduced or lost. The recovery of fertile soil through natural processes can take many decades or even centuries.

Soil compaction: Heavy machinery used for transporting and depositing mining waste, together with the weight of accumulated materials, can compact the underlying soil. This damages soil structure, reduces porosity, and limits the movement of air and water, creating unfavourable conditions for plant growth.

Erosion and sediment transport: Mining waste, particularly fine-grained tailings, can be easily transported by wind and water when vegetation cover is absent. This may result in the spread of contaminated dust and sediments to nearby agricultural land, residential areas, streams, and rivers.

Loss of soil fertility and productivity

Disruption of nutrient cycling: High concentrations of potentially toxic elements, unfavourable soil pH, and poor physical conditions can reduce the activity of soil microorganisms, including bacteria and fungi. This may slow down the decomposition of organic matter and disrupt

the natural cycling of nutrients essential for plant growth.

Loss of vegetation and productive land: Mining waste often contains little organic matter and may have poor physical and chemical properties that limit plant growth. As a result, previously productive agricultural land or forest areas may become sparsely vegetated or remain barren for long periods. However, natural vegetation can gradually develop on some mining waste deposits, particularly where environmental conditions are favourable.

The scale of the problem in CE region

In Central Europe, land and soil degradation caused by metal ore mining waste is mainly a legacy of historical mining activities, but it remains an important environmental problem. Although many mines have been closed, centuries of intensive mining of zinc, lead, silver, copper, iron, and other metal ores have left behind large quantities of mining waste stored in waste heaps and tailings ponds. These materials may contain high concentrations of potentially toxic elements, which can remain in the environment for centuries.

Although mining waste disposal sites usually occupy relatively limited areas, contamination can spread far beyond their boundaries through windblown dust, water erosion, and the transport of pollutants by surface water and groundwater. Due to Central Europe's long mining history, local administration may have to deal with numerous abandoned mining waste sites, including those for which no responsible owner or operator can be identified. Such sites may require environmental assessment, monitoring, and, where necessary, remediation.

The main regions of Central Europe affected by historical metal ore mining waste include:

Upper Silesia and Lesser Poland (Poland)

These regions are among the most heavily affected by historical mining and processing of zinc, lead, and silver ores in Central Europe. Centuries of mining and smelting activities, particularly around Bytom, Piekary Śląskie, Tarnowskie Góry, Olkusz, and Bukowno, have left large quantities of mining and processing waste. Soils in some of these areas contain elevated concentrations of potentially toxic elements, particularly cadmium, lead, zinc, and arsenic, sometimes exceeding national soil quality standards. Contaminants from historical waste disposal sites may spread into surrounding soils and water resources, creating potential risks for agricultural production and other land uses.

Ore Mountains (Erzgebirge/Krušné hory) and Harz Mountains (Germany and Czech Republic)

The Ore Mountains along the German-Czech border and the Harz Mountains in Germany have a long history of mining silver, tin, lead, zinc, uranium, and other metal ores. Historical mining activities have left numerous waste heaps and tailings disposal sites, some of which remain exposed

to erosion by wind and water. In certain areas, particularly around former mining and ore processing centres, surrounding soils and sediments contain elevated concentrations of arsenic, lead, and other potentially toxic elements. The release of contaminated dust, sediments, and mine drainage may continue to affect nearby agricultural land, forests, and water resources.

Central and Eastern Slovakia

Central and eastern Slovakia have a long history of mining copper, iron, mercury, and other metal ores. Important historical mining areas include Špania Dolina, Slovinky, and Rudňany. Former mining and ore processing activities have left waste heaps and tailings disposal sites that may contain elevated concentrations of arsenic, mercury, copper, and other potentially toxic elements. In some locations, erosion, contaminated drainage, and the transport of mining waste into nearby streams and rivers pose environmental risks. These problems may restrict certain land uses and require continued environmental monitoring and, where necessary, remediation.

Meža River Valley (Slovenia)

The Meža River Valley in northern Slovenia, close to the Austrian border, has a long history of lead and zinc mining and smelting, particularly around Mežica and Žerjav. Historical mining and industrial activities have caused widespread contamination of soils with lead and other potentially toxic elements. Contaminated dust and sediments have contributed to the spread of pollution beyond former mining and processing sites, affecting residential areas, agricultural land, and the surrounding environment. The region has required long-term environmental monitoring and remediation measures, including the replacement of contaminated topsoil in selected areas.

Styria and Carinthia (Austria)

Parts of Styria and Carinthia have a long history of metal ore mining and processing, including iron mining around Eisenerz and historical lead and zinc mining in Carinthia. Former mining activities have left waste rock heaps, processing residues, and, in some areas, smelting waste. Although the environmental impacts vary considerably between sites, erosion and the release of potentially toxic elements from historical waste deposits may affect surrounding soils, streams, and river sediments. Heavy rainfall and flooding can further contribute to the transport of contaminated materials, particularly in mountainous areas.

Sources of information to assess the problem on the local scale

The problem of soil and land degradation caused by historical waste disposal from local ore mining activities is relatively easy to identify based on knowledge of local mining history. Former ore mining sites, as well as historical waste dumps associated with ore extraction and processing, are generally known to local administration and residents, even if they date back to the Middle Ages or earlier and are now covered by vegetation. They can often still be identified as man-made

landforms and changes in the natural landscape.

Local administration can also obtain additional information on these forms of degradation from several other sources. In most Central European countries, the locations of former mines and associated waste disposal sites are relatively well documented, even where mining activities ceased many decades ago. However, information on the environmental impact of these sites, particularly soil and water contamination, may be less complete and require additional investigations.

The main sources of information available to local administration include:

Historical mining records and geological maps: National geological surveys, mining authorities, and regional archives often provide information on the locations of former mines, waste disposal sites, and the types of ores extracted. Historical maps can also help identify abandoned mining waste heaps that are no longer clearly visible in the landscape.

National and regional environmental databases: Environmental protection agencies and other public institutions collect information on contaminated land, soil quality, and groundwater contamination. These databases can help identify known contaminated sites and areas where environmental investigations have already been conducted. However, the availability and level of detail of this information vary between countries.

Land-use maps, aerial photographs, and satellite images: These sources can help identify mining waste disposal sites, estimate the areas they occupy, and assess changes in land use and vegetation cover. Comparing historical and current images can also reveal how former mining areas have changed over time.

Directly from residents, farmers, and other members of local communities who report potential environmental problems through public reporting systems, online platforms, or direct contact with municipal offices. Such reports may concern poor crop growth, unusual yellow or orange discoloration of water in streams and drainage channels, or excessive dust accumulation near former mining waste disposal sites. These observations can help identify areas potentially affected by historical mining activities and indicate where further environmental investigations may be needed.

Dumping of ashes and others coal combustion residues from power industry

Description the problem and forms of land and soil degradation

The disposal of coal combustion ash from thermal power plants can cause significant land and soil degradation by introducing potentially harmful substances into the environment, changing soil properties, and limiting the productive use of affected land. Coal-fired power plants generate large quantities of fly ash and bottom ash, which are often stored in ash disposal sites, including

dry waste heaps and ash ponds.

When these materials are not properly managed or protected, they may negatively affect surrounding soils and the environment through several main mechanisms:

Contamination with potentially toxic elements

Coal combustion ash may contain elevated concentrations of PTEs, which can accumulate in surrounding soils.

Fly ash and bottom ash may contain arsenic, cadmium, lead, copper, nickel, chromium, and zinc. These elements can enter surrounding soils through dust deposition, surface runoff, or the direct mixing of ash with soil.

High concentrations of PTEs may reduce soil microbial activity and negatively affect soil organisms. This can disturb natural biological processes that are important for maintaining soil fertility and supporting plant growth.

Leaching and groundwater contamination

Ash disposal sites may be exposed to rainwater infiltration, particularly where protective barriers and drainage systems are absent or insufficient.

Rainwater passing through ash deposits can dissolve and transport soluble salts and potentially harmful substances, producing contaminated water known as leachate.

Leachate may enter underlying soils and groundwater, potentially affecting water quality beyond the disposal site. The extent of contamination depends on the chemical composition of the ash, local geological conditions, groundwater movement, and the effectiveness of protective measures.

Loss of soil fertility and changes in soil properties

The deposition of large quantities of ash can cover natural soils and significantly change the physical and chemical properties of the affected land.

Coal ash often has an alkaline reaction and differs considerably from natural soil in its structure, nutrient content, and ability to retain water. When mixed with soil in large amounts, it may disturb soil pH, nutrient availability, and conditions for plant growth.

Large ash disposal sites occupy land that may previously have been used for agriculture, forestry, or other purposes. Where ash is deposited directly on fertile soil, the original soil profile may be buried or destroyed. Without appropriate reclamation, these areas may remain unsuitable for agricultural production or natural vegetation development for many years.

Wind erosion and dust deposition

Fly ash contains fine particles that can be easily transported by wind, particularly from dry, uncovered disposal sites.

During dry periods, exposed ash deposits and areas of ash ponds where water has evaporated may become important sources of airborne dust.

Wind can transport ash particles beyond disposal sites, causing their deposition on surrounding agricultural soils, forests, residential areas, and surface waters. This may contribute to the accumulation of potentially toxic elements in surface soils and create additional environmental and health concerns.

Potential radiological risks

Coal and lignite naturally contain small amounts of radioactive elements, including uranium, thorium, and their decay products, such as radium. During coal combustion, some of these elements may become concentrated in the resulting ash.

Accumulation of naturally occurring radioactive materials: Depending on the composition of the original coal and the combustion process, fly ash and bottom ash may contain higher concentrations of certain natural radionuclides than the original fuel.

Potential environmental risks: In some cases, large ash disposal sites may increase local radiation levels. However, the actual radiological risk depends on the concentrations of radionuclides, the amount of deposited ash, and possible exposure pathways. Specific measurements are required to determine whether a particular site poses a significant radiological risk.

The scale of the problem in CE region

Across Central Europe, land degradation caused by coal combustion residues, including fly ash, bottom ash, slag, and waste from hydraulic ash disposal, represents a significant environmental and land management challenge. This problem is largely a consequence of decades of coal-based energy production and heavy industrial activity. Large quantities of these wastes have accumulated in disposal sites, particularly in regions with a long history of coal-based energy production. Although coal-fired power plants are gradually being phased out in the European Union, existing waste disposal sites remain a long-term environmental concern. These sites contain technogenic materials that may contribute to soil contamination, restrict land use, and require appropriate management or remediation.

Central European regions most affected by coal combustion waste disposal are:

Upper Silesia (Poland)

This is one of the main centres of the problem on a macro-regional scale. The concentration of coal-fired power generation and heavy industry has led to the creation of numerous ash and slag disposal sites, some of which contain mixtures of different coal combustion residues. This has resulted in permanent alterations to soil profiles, potentially elevated concentrations of heavy metals (zinc, lead, cadmium, and chromium) in the vicinity of former and existing disposal sites, and the need for costly, long-term reclamation of affected areas.

Moravian-Silesian Region (Czech Republic)

The Czech counterpart of Polish Upper Silesia, particularly around Ostrava and Karviná. For over a century, this industrial region relied heavily on coal-based energy production, resulting in the accumulation of large quantities of coal combustion residues, often deposited in former excavation pits or surface disposal sites.

German lignite regions (Lusatia and Central Germany)

German lignite mining and combustion regions (e.g., around Leipzig and Cottbus) have accumulated enormous quantities of coal combustion residues. Although Germany has implemented extensive reclamation programmes, including the conversion of former open-pit mining areas into lakes and recreational landscapes, large areas affected by ash disposal have undergone substantial physical and chemical alterations to soils and underlying geological materials.

Wałbrzych Region / Lower Silesia (Poland)

Although hard coal mining in the Wałbrzych and Nowa Ruda areas has ceased, historical emissions from coal combustion and old ash disposal sites associated with local heating and industrial facilities have left a significant impact on the chemical properties of surrounding soils.

One of the main problems in the above-mentioned regions is their high population density. In Central Europe, many historical ash disposal sites are located close to large urban agglomerations, increasing the risk of secondary dust emissions and the migration of potentially toxic substances into soil and groundwater, including groundwater resources used for drinking water supply.

A second important problem is climate change. Increasingly frequent and prolonged droughts in Central Europe may cause exposed ash deposits and dried-out ash ponds to become more susceptible to wind erosion. This can lead to the transport of contaminated dust and its deposition on surrounding agricultural soils, potentially affecting areas located several kilometres from the original disposal sites.

Sources of information to assess the problem on the local scale

For local authorities, identifying historical waste disposal sites, assessing their environmental condition, and considering potential risks in land-use planning are essential steps towards safe and sustainable management of degraded land. The presence of an ash disposal site does not automatically indicate soil contamination. However, accumulated combustion residues can cause physical degradation of the land, restrict its use, and, under certain conditions, release contaminants into the surrounding soil and groundwater. The extent of these environmental impacts depends on the chemical and physical properties of the waste, as well as the disposal and storage conditions. Historical coal combustion waste disposal sites should therefore be identified and assessed for potential environmental risks before decisions on future land use are made. Not all

such sites require remediation, but their potential environmental hazards should be identified and evaluated to ensure safe and sustainable land management.

Locating coal combustion waste disposal sites within local administrative boundaries is relatively straightforward. Their locations are generally well documented, particularly in the case of ash disposal sites, settling ponds, and modern landfills. A somewhat more challenging issue is determining the spatial extent of their environmental impact. Publicly available geochemical maps maintained by national geological surveys can be helpful in this regard, as they may reveal contamination halos around historical waste disposal sites.

This can be particularly useful in the case of old, historical disposal sites located in former mining pits, subsidence basins, or natural depressions. Such historical or illegal disposal sites may lack sufficient documentation to determine their precise locations. It is important to remember, however, that the analysis of geochemical maps in urban and post-industrial areas does not always allow contamination to be clearly attributed to a specific waste disposal site. Elevated concentrations of contaminants may also result from historical atmospheric deposition or reflect the natural geochemical background. Furthermore, two main mechanisms of contaminant migration from waste disposal sites should be considered: the transport of dissolved substances with water and the wind-driven dispersal of dust from the landfill surface. The spatial extent of contamination associated with these two processes may differ significantly.

Dumping of non-degradable municipal solid waste (MSW)

Description the problem and forms of land and soil degradation

Municipal waste (commonly referred to as municipal solid waste, or MSW) is the everyday waste (trash or garbage) generated by households, commercial establishments, and institutions within a municipality. It consists mainly of materials and items that are discarded during daily activities.

Municipal waste is highly diverse and can generally be divided into several main categories:

Biodegradable and organic waste: Food scraps, kitchen waste, yard trimmings, and garden waste.

Recyclable materials: Paper, cardboard, glass bottles, aluminium and steel cans, and certain types of plastic.

Non-biodegradable plastics and synthetic materials: Plastic bags, wrappers, single-use packaging, synthetic textiles, and other disposable items.

Bulky waste: Discarded furniture, mattresses, and large household appliances (white goods).

Institutional and commercial waste: Waste generated by schools, offices, hotels, and retail establishments that is similar in nature and composition to household waste.

Municipal waste disposal sites can cause land and soil degradation through a combination of chemical contamination, physical alteration, and biological disruption. When large volumes of waste, including organic, hazardous, and non-biodegradable materials, are concentrated in one area, they can trigger complex physical, chemical, and biological processes that significantly alter the surrounding environment. In particular, non-biodegradable waste, including plastics present in MSW, can contribute to soil and land degradation by altering soil structure, introducing potentially harmful substances, and disrupting soil biological communities. Because most conventional plastics are highly resistant to biodegradation, they can persist in the environment for decades or even centuries, contributing to long-term environmental damage.

This manifests itself in the following ways:

Destruction of soil physical structure

Disruption of root growth: Non-biodegradable waste can form hard, impenetrable layers underground. Plant roots may be unable to penetrate these barriers, which restricts root development, stunts plant growth, and reduces agricultural yields.

Soil compaction and loss of porosity: The enormous weight of accumulated waste, combined with the use of heavy machinery at disposal sites, can compress the underlying soil. This damages soil structure and reduces the pore spaces needed for air and water circulation, leading to poor soil aeration and reduced water permeability.

Altered hydrological conditions: Landfills can disrupt natural surface runoff and drainage patterns. This may cause excessive water accumulation in some adjacent areas and increased drying in others, potentially accelerating soil erosion.

Removal of fertile topsoil: The construction of waste disposal sites often involves excavating and removing the fertile, organic-rich topsoil layer. This significantly alters the natural soil profile and may expose less fertile subsoil, reducing the land's potential for agricultural use.

Accelerated soil erosion: The accumulation of non-biodegradable waste, including plastics, can disrupt soil structure and inhibit vegetation growth. As a result, exposed and poorly protected soil becomes more vulnerable to erosion by water and wind.

Chemical contamination through leachate and waste degradation

Formation of toxic leachate: Rainwater filtering through layers of municipal waste dissolves soluble chemicals and carries contaminants, producing a potentially hazardous liquid known as leachate. This liquid is often dark in colour and may contain high concentrations of organic substances, dissolved salts, heavy metals, and other pollutants.

Soil acidification: The decomposition of organic waste in landfills produces organic acids that can lower the pH of leachate and, under certain conditions, surrounding soils. This may negatively affect soil fertility and create unfavourable conditions for plant growth.

Heavy metal contamination: Leachate may contain potentially toxic elements, including

lead, mercury, cadmium, and arsenic, originating from discarded batteries, electronic waste, and other hazardous materials present in municipal waste. These contaminants can accumulate in soils or migrate into groundwater, depending on soil properties and environmental conditions.

Leaching of hazardous chemical additives: Some plastics contain chemical additives, such as phthalates, bisphenol A (BPA), and certain metal-based compounds, which are used to improve their flexibility, durability, or other properties. Over time, some of these substances may be released from discarded plastics and enter the surrounding soil or water, contributing to environmental contamination.

Accumulation of microplastics: Over time, exposure to sunlight (UV radiation), temperature changes, and physical weathering can break larger plastic items into smaller particles known as microplastics and nanoplastics. These particles can accumulate in soil, where they may persist for long periods and affect its physical properties and biological activity.

Adsorption of persistent organic pollutants (POPs): Microplastics can adsorb certain organic contaminants, including some pesticides and industrial chemicals, from their surroundings. These substances may accumulate on plastic particle surfaces and potentially influence their transport and distribution in soil. However, the extent of this process depends on the type of plastic, the properties of the contaminants, and local environmental conditions.

Disruption of soil biological activity

Harmful effects on beneficial soil organisms: Earthworms, ants, and termites may ingest microplastics present in contaminated soils. Depending on the type, size, and concentration of plastic particles, this can cause physical damage, digestive problems, reduced reproduction, and, in severe cases, increased mortality. Earthworms play an important role in soil aeration, organic matter decomposition, and nutrient cycling. A decline in their populations can therefore negatively affect soil health.

Alteration of the soil microbiome: The accumulation of plastics and other waste materials can alter soil moisture conditions, pH, and other soil properties, potentially disrupting communities of beneficial bacteria and fungi. These changes may affect the decomposition of organic matter and nutrient cycling, leading to a gradual decline in soil fertility.

Oxygen depletion caused by landfill gases: As organic waste decomposes under oxygen-limited conditions, it generates landfill gases, primarily methane and carbon dioxide. The migration of these gases into surrounding soils can reduce oxygen availability, creating unfavourable conditions for aerobic microorganisms and soil fauna, including earthworms.

Microbial imbalance: The introduction of pathogens and potentially harmful chemical substances from municipal waste can alter the natural composition of soil microbial communities. Beneficial bacteria and fungi involved in organic matter decomposition and nutrient cycling may decline, while microorganisms adapted to contaminated or oxygen-poor conditions may become

more abundant. These changes can disrupt natural soil biological processes and reduce soil fertility.

Long-term land degradation and loss of land-use potential

Long-term restrictions on land use: Even after a landfill is closed and capped, the underlying waste may remain unstable and contain potentially harmful substances. Ongoing gas emissions and the possible migration of contaminants can restrict the use of the land for agriculture, forestry, or residential development for many years. However, some former landfill sites can be safely reused after appropriate environmental assessment and reclamation.

Bioaccumulation of contaminants: Vegetation growing near contaminated waste disposal sites may absorb potentially toxic elements, including heavy metals, from the soil. These substances can accumulate in plant tissues and may be transferred to animals that feed on contaminated vegetation, potentially affecting local wildlife and agricultural food production.

Creation of degraded and abandoned land: Areas used for uncontrolled waste dumping can become heavily contaminated and lose much of their ecological and economic value. Soil degradation and the presence of buried waste may severely restrict future land use, including agriculture, forestry, and urban development. Restoring such areas may require costly and long-term remediation or reclamation measures.

Food chain contamination: Crops grown in soils contaminated by plastic waste may absorb certain chemical additives released from plastics and, under specific conditions, very small plastic particles, particularly nanoplastics, through their roots. These substances may enter edible plant tissues and potentially be transferred to animals and humans through the food chain. The extent of this transfer and the associated health risks depend on the type and concentration of contaminants and their bioavailability.

The threats and processes described above mainly concern old, unreclaimed, or poorly managed municipal waste disposal sites. However, similar mechanisms of soil degradation also occur at illegal waste dumps, which are often located in forests, wastelands, abandoned mining pits, and other uncontrolled locations. Although typically small in size, illegal dumps can generate specific environmental threats that are often more difficult to control. While the scale of an individual illegal dump is generally smaller than that of a formal landfill, the absence of protective measures means that contamination of the surrounding soil and environment can occur more directly and rapidly.

Due to the lack of protective barriers and proper waste management, illegal dumps can cause several environmental problems:

Direct infiltration of contaminants into the soil: Unlike modern, properly engineered landfills, which are generally equipped with protective liners made of geomembranes and compacted clay, illegal dumps lack such safeguards. Rainwater passing through the waste can generate contaminated leachate that infiltrates directly into the underlying soil and may eventually

reach groundwater, depending on local geological and hydrological conditions.

Formation of local contamination hotspots: Discarded batteries, paint residues, used engine oil, and electronic waste (e-waste) may release potentially toxic substances as they deteriorate. Heavy metals and other contaminants, including cadmium, lead, and mercury, can accumulate in the surrounding soil, creating local contamination hotspots that may persist for many years and require remediation.

Scattered and widespread land degradation: Illegal dumps frequently occur along roads, in forests, drainage ditches, and at the edges of agricultural fields. Their scattered distribution can result in numerous small areas of soil contamination and habitat degradation across a municipality. Unlike a single large landfill, these dispersed sites are often difficult to identify, monitor, and manage effectively.

Rapid dispersal of plastic waste: Lightweight materials, such as plastic bags and expanded polystyrene (Styrofoam), are often left exposed at illegal dumps. Wind, surface runoff, and animals can transport these materials into surrounding forests, fields, and watercourses. Over time, larger plastic items may break down into microplastics, contributing to the contamination of nearby agricultural and forest soils.

The scale of the problem in CE region

In Central Europe, the main challenge is not modern, properly managed waste disposal facilities, but rather the numerous older municipal landfills established before the adoption of the EU Landfill Directive in 1999 and its subsequent implementation in Member States. In some Central European countries, including Poland, the Czech Republic, Slovakia, and Hungary, the number of such sites is historically high, partly due to delays in developing modern waste management and recycling systems during the 1990s and 2000s. Many of these municipal landfills, although already closed, may still affect the surrounding environment. Older facilities often lacked modern protective barrier systems, such as high-density polyethylene (HDPE) geomembranes and compacted clay liners. As a result, contaminated leachate containing heavy metals, organic compounds, and other potentially harmful substances may have migrated, and in some cases may continue to migrate, into surrounding soils and groundwater. Earlier European estimates suggested that the annual costs of managing contaminated sites could reach approximately €4.5 – 5.5 billion (Panagos et al., 2025), highlighting the substantial financial burden associated with historical soil contamination. These costs can place a significant financial burden on local authorities, particularly in regions with numerous historical waste disposal sites.

Illegal dumping of municipal waste also remains a serious environmental problem in Central Europe, particularly in rural and suburban areas and forests. At illegal dumps, municipal plastic

waste, such as bottles and plastic packaging, is often mixed with hazardous materials, including discarded household appliances, batteries, and construction chemicals. The absence of protective measures and proper waste management can result in the direct release of PTEs and other contaminants into the soil. Studies of soils affected by illegal waste dumping have reported negative effects on soil fauna, including earthworms and mites, as well as reduced microbial enzymatic activity associated with organic matter decomposition and nutrient cycling. The severity of these effects depends on the composition of the waste, contaminant concentrations, and local soil conditions.

Sources of information to assess the problem on the local scale

Assessing the scale of land and soil degradation associated with legally established municipal landfills is relatively straightforward, as even older sites are generally well documented. Illegal waste dumps, however, pose a much greater challenge, particularly when assessing their number, location, and environmental impact. In such cases, reports from law enforcement agencies and information provided by local residents can be valuable sources of information. Mobile applications and online reporting platforms introduced by local authorities are examples of good practices already implemented in some municipalities. Municipal surveillance camera systems, including cameras installed in urban forests and other areas prone to illegal dumping, can also help identify illegal waste disposal sites. By combining these sources of information, local authorities can develop a relatively comprehensive inventory of illegal dumps within their municipality. Although identifying and locating such sites should not pose major difficulties where effective reporting and monitoring systems are in place, assessing the actual extent of soil contamination and degradation may require additional field inspections and environmental investigations.

Land and soil degradation in former quarries and areas affected by natural resource extraction

Description the problem and forms of land degradation

Soil and land deformation in former quarries and open-pit mining areas where rocks, aggregates, and ceramic clays were extracted (such as former clay pits associated with brickworks) is primarily caused by mechanical disturbance of the ground, removal of geological materials, and changes in hydrological conditions following the cessation of mining activities. Unlike underground mining, where land subsidence may result from the collapse of underground voids, open-pit extraction directly modifies the land surface and its geological structure. The resulting deformation is mainly controlled by the geometry and stability of excavation slopes, the uneven settling of

loosely compacted backfill materials, and changes in local groundwater levels, including groundwater rebound after mining operations cease.

In areas affected by open-pit extraction of natural resources, soil degradation is not limited to surface deformation. The removal of natural soil horizons, loss of soil organic matter (humus), destruction of soil structure, and changes in soil water retention and drainage properties are also significant. In former clay pits, gravel pits, and sand pits, these processes may pose an even greater challenge to land restoration than slope instability itself. The extent and severity of these processes depend on the type of raw material extracted, the depth and geometry of the excavation, local geological and hydrological conditions, and whether appropriate land reclamation measures have been implemented.

Quarry walls and the slopes of former open-pit mines may undergo gradual deformation and instability over time due to changes in the stress conditions of the surrounding rock or soil. The removal of large volumes of rock, gravel, or clay during extraction reduces the pressure exerted by the excavated material and alters the distribution of stresses within the surrounding geological formations. In some cases, the rock mass responds through stress relief, resulting in slight upward or lateral movements towards the excavation. These processes may contribute to the development or widening of fractures, gradually weakening the stability of quarry walls and excavation slopes.

Former clay pits associated with brickworks are particularly susceptible to moisture-related deformation. Clay-rich materials may undergo repeated swelling and shrinkage as their moisture content changes. Following the cessation of mining activities, alternating wetting and drying cycles can promote cracking, weakening, and progressive slope instability, potentially leading to slumping or rotational landslides along shear surfaces.

In hard-rock quarries, such as those developed in limestone or granite, slope stability is largely controlled by the geological structure of the rock mass, particularly the orientation and characteristics of joints, fractures, bedding planes, and other discontinuities. Rainwater infiltrating these fractures may increase water pressure and reduce slope stability, potentially triggering the detachment of large rock blocks, sudden rockfalls, or gradual slope failures. The likelihood and severity of these processes depend on local geological conditions, slope geometry, groundwater conditions, and the degree of weathering of the exposed rock.

Many former aggregate pits and clay extraction sites associated with brickworks have been partially or completely backfilled with excavation waste, overburden, or construction debris. Such “reclaimed” areas may remain susceptible to secondary ground deformation, particularly where backfilling was carried out without adequate compaction and geotechnical control. Materials used for backfilling, including excavated soil, glacial till, and crushed rock fragments, may initially contain a high proportion of void spaces when deposited loosely. Over time, these materials gradually settle under their own weight as particles rearrange and the volume of void spaces

decreases. This process may result in differential settlement, with some parts of the backfilled excavation subsiding more rapidly than others, potentially creating local depressions or uneven ground surfaces. Additional settlement may occur when loosely deposited backfill becomes saturated with water. In certain moisture-sensitive soils, wetting can reduce the forces holding soil particles together, causing a sudden reduction in volume, known as collapse settlement. Where groundwater was artificially lowered during extraction, the cessation of pumping may lead to a rise in groundwater levels and saturation of previously unsaturated backfill materials. Depending on their composition, density, and structure, these materials may undergo further settlement, potentially causing rapid ground subsidence and damage to buildings, roads, or other infrastructure constructed on the reclaimed land.

The creation of an open-pit excavation can significantly alter local hydrogeological conditions, particularly where mining activities intersect shallow groundwater aquifers. Sand and gravel extraction may disrupt natural groundwater flow patterns and change groundwater levels in the surrounding area. Under certain conditions, groundwater flowing towards the excavation can transport fine soil particles, leading to internal erosion. Where concentrated seepage develops and progressively removes soil particles, a process known as piping may occur, creating subsurface channels and potentially causing localized ground settlement or the formation of small sinkholes near the excavation edges.

In abandoned sand and aggregate processing areas, deposits of fine-grained tailings and loosely packed sands may remain saturated with water. Under specific conditions, such as rapid changes in pore-water pressure, dynamic loading, or vibrations, these materials may become unstable and undergo liquefaction or other forms of strength loss. Liquefaction occurs when saturated, susceptible soils experience a substantial reduction in effective stress and shear resistance, potentially resulting in ground deformation, lateral spreading, or localized settlement. These processes may threaten the stability of reclaimed land and nearby infrastructure, particularly where the geological and groundwater conditions have not been adequately assessed.

The stability of abandoned quarry walls and excavation slopes is an important consideration in land-use planning and public safety management. Former extraction sites, particularly those located near residential areas, roads, or recreational facilities, may require periodic inspections and, where signs of instability are identified, detailed geotechnical assessments. Visible cracks, slope deformation, falling rock fragments, and changes in groundwater seepage may indicate developing instability. Identifying such hazards at an early stage can help municipalities prevent accidents, restrict access to dangerous areas, and determine appropriate land restoration or reuse measures.

The scale of the problem in CE region

At the regional scale in Central Europe, land deformation and soil degradation associated with former quarries and open-pit extraction sites, including aggregate pits, clay pits, and former brickworks, represent not only local geotechnical problems but also broader challenges for spatial planning, environmental management, and sustainable land use. Central Europe has a long history of mineral resource extraction, with numerous historical and active quarries and clay extraction sites, particularly in industrialized regions of Poland, the Czech Republic, eastern Germany, Hungary, and Austria.

As Central European regions are increasingly affected by climate change, particularly more frequent periods of drought and episodes of intense rainfall, the stability of abandoned quarries and clay pits is becoming an increasingly important concern. Heavy rainfall may trigger or reactivate landslides and other mass movements along fractured quarry walls and unstable slopes of former clay pits, potentially threatening nearby roads, railway lines, buildings, and other infrastructure. Changes in groundwater conditions may also affect the local water balance. In some abandoned open-pit mines, the cessation of groundwater pumping can lead to groundwater rebound, flooding of excavations, and the formation of artificial lakes. Depending on local hydrogeological conditions, these processes may affect adjacent agricultural land, settlements, and groundwater resources, requiring appropriate monitoring and water management measures.

At the same time, former mining and extraction sites offer considerable opportunities for environmental restoration, biodiversity conservation, and alternative land uses. In many Central European regions, abandoned quarries and clay pits have become valuable habitats through natural ecological succession, even without planned reclamation measures. For example, dry limestone quarries may provide suitable conditions for rare xerothermic grassland communities and associated animal species, while former clay pits and brickworks, particularly where low-permeability clay layers restrict water infiltration, may gradually develop into wetlands, ponds, or small water retention areas. Such sites can contribute to local biodiversity and, under suitable conditions, support water retention and climate adaptation.

Due to their distinctive landscape features and ecological value, some former extraction sites can also be successfully adapted for recreational, educational, tourism, or cultural purposes. Following appropriate safety assessments and, where necessary, reclamation or restoration measures, these areas may be transformed into nature parks, educational trails, recreational lakes, or open-air cultural facilities, such as amphitheatres.

Sources of information to assess the problem on the local scale

For local authorities, the main challenge is therefore not only to identify and manage the

environmental and geotechnical risks associated with former extraction sites, but also to recognize their potential contribution to sustainable land management, biodiversity protection, and local development.

Former extraction sites filled with uncontrolled or poorly compacted materials may pose significant challenges for spatial planning and future land development. Even where the land surface appears stable and has been covered with vegetation, gradual or differential settlement may continue for many years. Before such areas are designated for residential, commercial, or infrastructure development, available historical records of excavation and backfilling activities should be reviewed, and appropriate geotechnical investigations should be carried out. Particular attention should be paid to the composition and thickness of backfill materials, groundwater conditions, and visible signs of ground deformation.

Changes in groundwater conditions around former sand and gravel pits should be considered when assessing land stability and planning future land use. Particular attention should be paid to abandoned excavations, waterlogged backfill materials, and areas where groundwater seepage or uneven ground settlement has been observed. Historical mining records, groundwater monitoring data, and geological maps can provide useful information for identifying potentially unstable sites. Where significant risks are suspected, targeted hydrogeological and geotechnical investigations may be necessary before approving new development or implementing land restoration measures.

For local administration, former quarries and open-pit mining sites represent both an environmental management challenge and an opportunity for land restoration and reuse. Assessing slope stability, soil conditions, groundwater levels, and the degree of natural vegetation recovery is essential for identifying potential environmental and safety risks and determining suitable future land uses. Depending on local conditions, these areas may be restored for recreational purposes, water retention, biodiversity conservation, or selected forms of non-food agricultural production. Particular attention should be paid to areas where natural ecological succession has created valuable habitats, as these may offer opportunities for biodiversity conservation and nature-based solutions without requiring extensive engineering interventions. Decisions on future land use should balance public safety, environmental protection, climate adaptation, and local development needs.

For local authorities, the management of former quarries and extraction sites should be based on an integrated assessment of geotechnical stability, groundwater conditions, ecological value, and potential future land uses. Municipalities can use historical mining records, geological and hydrogeological maps, environmental inventories, and spatial planning databases to identify abandoned extraction sites and assess their current condition. Identifying areas potentially affected by soil and land degradation associated with former quarries and other extraction sites should be relatively straightforward, as the locations of many such sites, including historical ones, are generally known to local authorities and residents. These sites can often be identified on aerial

photographs and satellite imagery and may also be marked on geological, environmental, and historical land-use maps available through national and regional databases.

Land and soil degradation in flooded areas

Description the problem and forms of land and soil degradation

Flooding can significantly affect land conditions and soil quality, triggering various physical, chemical, and biological processes of soil degradation. The nature and severity of these effects depend on flood intensity and duration, water quality, soil properties, and the time elapsed since the flooding event. In recently flooded areas, physical damage, sediment deposition, waterlogging, and potential contamination are often the most immediate concerns. In areas affected by historical flooding, some consequences may persist for years, particularly where prolonged waterlogging, soil erosion, contamination, or inadequate land restoration have affected soil functions.

Short- and medium-term effects in recently flooded areas.

In areas affected by flooding within the past few weeks or years, soils may show visible evidence of erosion, sediment deposition, prolonged saturation, or contamination. The most important effects include:

• Water erosion and surface scouring: Fast-flowing floodwater can remove the fertile topsoil, including the humus-rich horizon containing much of the soil organic matter and essential plant nutrients. Severe erosion may expose less fertile subsoil or remove parts of the soil profile entirely

• Siltation and sediment deposition: Floodwaters may deposit layers of sand, silt, clay, or gravel on agricultural land. While fine river sediments can sometimes improve soil fertility, thick deposits of coarse sand or gravel may bury fertile topsoil, reduce agricultural productivity, and require costly restoration measures.

• Surface sealing and crust formation: Fine sediment particles deposited by floodwater may form a dense surface layer as the soil dries. This can reduce water infiltration, restrict soil aeration, hinder seedling emergence, and increase surface runoff during subsequent rainfall events.

• Soil structural degradation and compaction: Prolonged saturation may weaken soil aggregates and reduce structural stability. Following flooding, agricultural machinery operating on wet soils can cause severe compaction, reducing soil porosity, water infiltration, and root development. These effects may persist after the soil has dried.

• Chemical and biological contamination: Floodwaters may transport untreated sewage, petroleum products, industrial chemicals, pesticides, and potentially toxic elements, including

heavy metals and metalloids. Contaminated sediments may accumulate on agricultural land, recreational areas, and residential properties. Floodwater may also introduce pathogenic microorganisms, creating potential health risks and temporarily restricting the safe use of affected land.

The distant past (long-term effects)

In areas affected by floods many years or decades ago, certain forms of soil degradation may persist, particularly where severe erosion, prolonged waterlogging, sediment deposition, or contamination have occurred and appropriate restoration measures have not been implemented. Potential long-term effects include:

• Persistent depletion or loss of soil fertility: Severe erosion and the removal of nutrient-rich topsoil may cause long-term reductions in soil fertility and agricultural productivity. Prolonged waterlogging can also promote nutrient losses through leaching and denitrification, particularly affecting nitrogen availability. The extent of nutrient depletion depends on soil properties, flood conditions, and subsequent land management.

• Changes in soil acidity: Prolonged flooding and subsequent drainage may alter soil chemical conditions and influence soil pH. In certain soils, particularly those containing reduced sulfur compounds, exposure to oxygen after drainage can lead to strong acidification. However, flooding does not necessarily cause soil acidification, and its effects depend on the soil's mineralogical composition and buffering capacity.

• Secondary salinization (under certain conditions): In coastal areas affected by seawater flooding, or in regions where floodwaters contain elevated concentrations of dissolved salts, salinization may occur. Poor drainage and subsequent evaporation can promote salt accumulation in the upper soil horizons, reducing water availability to plants and limiting agricultural productivity.

• Persistent waterlogging and changes in soil hydrological conditions: Flooding may be associated with long-term changes in drainage conditions, particularly where sediment deposition, river channel modification, or alterations to local groundwater flow have occurred. Poorly drained areas may develop persistent waterlogging and reducing conditions, resulting in the formation or intensification of hydromorphic soil features, including gleying. These conditions can restrict root development and influence nutrient cycling and organic matter decomposition.

• Changes in soil biodiversity and biological activity: Prolonged waterlogging and oxygen deficiency may reduce the activity or abundance of some soil organisms, including earthworms, aerobic microorganisms, and certain mycorrhizal fungi. Repeated flooding or persistent waterlogging can alter soil microbial communities and biological processes. Recovery depends on the duration and frequency of flooding, soil properties, vegetation, and subsequent land management, and may require considerable time in severely affected soils.

The scale of the problem in CE region

Flooding represents a significant environmental challenge in Central Europe, affecting land stability, soil quality, agricultural productivity, and infrastructure. Major flood events in recent decades, particularly those in 1997, 2002, 2013, and 2024, have demonstrated the vulnerability of many Central European regions to extreme rainfall and river flooding. Climate change, changes in land use, and increasing pressure on floodplains may further intensify flood-related environmental risks.

Central Europe faces a particular combination of historical industrial pollution and flood-related hazards. Long-term industrial development, mining, and intensive land use have left numerous potentially contaminated sites, including brownfields, former industrial facilities, mining areas, and waste disposal sites. During floods, contaminated soils and sediments may be eroded, transported, and redeposited in agricultural fields, river valleys, and other flood-prone areas. This can lead to the redistribution and accumulation of potentially toxic elements, including heavy metals and metalloids, as well as other chemical pollutants, creating long-term risks for soil quality and land use.

In Central Europe, several regions are particularly exposed to different forms of flood-related land and soil degradation:

Lower Silesia, Opole, and Silesia (Poland)

The Oder River basin and its tributaries are among the areas most affected by major floods in southwestern Poland, particularly during the events of 1997, 2010, and 2024. These regions combine significant flood exposure with a long history of industrial activity, mining, and intensive agricultural land use. Flood-related soil degradation may include the erosion of fertile topsoil, deposition of coarse sediments, prolonged waterlogging, and redistribution of contaminants originating from industrial areas and historically polluted river sediments. Similar risks may occur in flood-prone areas of the upper Vistula basin, particularly in industrialized parts of Silesia.

Moravian-Silesian Region and Central Bohemia (Czech Republic)

The Czech Republic has experienced several major flood events, particularly in 1997, 2002, 2013, and 2024, affecting different river basins, including the Oder, Morava, and Elbe. In agricultural areas, intense rainfall and rapid surface runoff may cause severe water erosion, the removal of fertile topsoil, and the formation of erosion gullies, particularly on sloping fields with insufficient vegetation cover. In industrialized areas, such as the Moravian-Silesian Region, flooding may also contribute to the redistribution of historical industrial contaminants. The severity of soil degradation depends on local topography, land use, soil properties, and flood characteristics.

Pannonian Basin: Hungary and Eastern Austria

Lowland areas along the Danube and Tisza rivers are particularly susceptible to extensive river flooding, prolonged waterlogging, and changes in soil drainage conditions. In poorly drained agricultural areas, prolonged saturation may reduce soil aeration, affect soil structure, and restrict agricultural productivity. Under specific conditions, particularly where saline groundwater or salt-rich sediments are present, changes in water balance may also contribute to secondary soil salinization.

The Tisza River basin is additionally affected by the historical legacy of mining and industrial activities in its upstream catchment areas. Flood events may remobilize contaminated river sediments and redistribute potentially toxic elements across downstream floodplains. Such processes can create persistent environmental risks for agricultural soils and aquatic ecosystems.

Eastern and Northern Germany, Particularly Saxony

Parts of eastern Germany, particularly Saxony and the Elbe River basin, have experienced major floods, including those in 2002 and 2013. Flooding may cause extensive soil erosion, sediment deposition, prolonged waterlogging, and damage to agricultural land. In some areas, floodwaters may also redistribute contaminants associated with historical mining, industrial activities, and polluted river sediments. Long-term consequences depend on the extent of soil erosion, sediment characteristics, contamination levels, and subsequent land management practices.

Alpine Foothills: Northern Italy and Slovenia

Mountainous and foothill regions of northern Italy and Slovenia are particularly exposed to intense rainfall, flash floods, rapid surface runoff, and associated landslides. In Liguria and Piedmont, steep slopes and narrow river valleys can promote severe water erosion, sediment transport, and localized destruction of soil profiles during extreme rainfall events.

Slovenia has also experienced major flood events, including the severe floods of August 2023, which affected several river basins and caused extensive damage to agricultural land and infrastructure. Flood-related degradation may include the erosion of fertile alluvial soils, deposition of coarse sediments, riverbank erosion, and landslides. In these regions, the interaction between steep terrain, intense precipitation, and land-use practices plays a particularly important role in determining the severity of soil and land degradation.

Sources of information to assess the problem on the local scale

For local authorities, identifying and assessing flood-related soil degradation is essential for spatial planning, agricultural land management, and environmental risk prevention. Flood hazard and risk maps, historical flood records, soil maps, and environmental monitoring databases can help identify areas potentially affected by erosion, sediment deposition, prolonged waterlogging, or contamination. Following major floods, priority should be given to assessing soil conditions in

agricultural areas, residential zones, and locations where floodwaters may have transported pollutants from industrial facilities or contaminated sediments. In areas affected by repeated or historical flooding, targeted soil investigations may be necessary to determine whether long-term degradation or contamination restricts future land use.

Land and soil degradation in military areas

Description the problem and forms of land and soil degradation

Military activities on active and former military training grounds contribute to land and soil degradation through severe physical, chemical, and biological disturbances. These impacts can profoundly alter soil structure and properties, often transforming previously fertile soils into heavily contaminated and ecologically degraded areas, with adverse effects persisting for decades or even centuries.

The main mechanisms of land and soil degradation in military areas include:

Physical degradation and bombturbation

Soil horizon mixing: Artillery shells, bombs, and missile explosions physically disrupt the soil, causing a specific form of soil disturbance known as bombturbation (Hupy & Schaetzl, 2006). This process results in the mixing and inversion of soil horizons, the exposure of subsurface materials, and the formation of deep craters that can permanently alter the landscape.

Soil compaction: The repeated movement of heavy military vehicles, such as tanks, armoured personnel carriers, and transport trucks, causes significant soil compaction. This alters the natural soil structure by reducing pore space, thereby restricting air circulation, water infiltration, and root penetration.

Soil erosion: Compacted and cratered soils often exhibit reduced water infiltration capacity, leading to increased surface runoff. Combined with the destruction of vegetation cover by fires, military activities, or land clearing, this accelerates the loss of topsoil through water and wind erosion, potentially resulting in severe land degradation and, in susceptible dryland environments, desertification.

Chemical contamination

Military areas can become significant sources of persistent and potentially hazardous chemical contaminants that accumulate in soils and may migrate into surrounding environments.

Explosive residues: The use, detonation, and incomplete combustion of munitions can release toxic explosive compounds, including nitroaromatic substances such as TNT (2,4,6-trinitrotoluene) and DNT (dinitrotoluene), into the surrounding environment. Some of these compounds are resistant to natural biodegradation and may persist in soils for extended periods.

Concentration of PTEs: Spent ammunition, munition fragments, and abandoned or destroyed

military equipment can introduce potentially toxic elements, including lead (Pb), antimony (Sb), copper (Cu), zinc (Zn), and, in specific military applications, depleted uranium (U), into the soil. These elements do not undergo biodegradation and may accumulate in soils, alter soil chemical and biological properties, and pose a risk of migration into groundwater, depending on their chemical forms and environmental conditions.

Petroleum hydrocarbons and solvents: Routine military operations, maintenance activities, fuel storage, and the destruction of military vehicles can result in the release of petroleum hydrocarbons, lubricants, and industrial solvents into the soil. These substances may adversely affect soil biological activity and contaminate groundwater.

Biological and ecological degradation

Disruption of soil biological communities: The combined effects of physical disturbance, elevated temperatures associated with fires and explosions, and chemical contamination can significantly reduce the abundance, diversity, and activity of soil microorganisms and soil fauna, including beneficial bacteria, fungi, and earthworms.

Loss of soil functions and ecosystem services: The degradation of soil biological communities can impair essential soil functions, including nutrient cycling, organic matter decomposition, carbon sequestration, and natural regeneration processes. Consequently, severely degraded soils may lose their capacity to support agricultural production and natural vegetation recovery without appropriate remediation or restoration measures.

The scale of the problem in CE region

In Central Europe, land and soil degradation associated with former, abandoned, and active military sites represents a significant and complex environmental and land management challenge.

The scale of this problem is largely related to the region's turbulent history during the 20th century, including World War II, the extensive military infrastructure developed during the Cold War, and the subsequent withdrawal of Soviet troops in the early 1990s. As a result, thousands of former military sites, often referred to as "military brownfields", have been left across Central Europe, many of which remain contaminated and environmentally degraded (Gordienko 2025). Contaminated military brownfields are very common in the CE region. These former military sites constitute a specific and challenging category of potentially degraded land, often limiting opportunities for their safe redevelopment or alternative use. Numerous research projects and initiatives (Morar et al. 2016), together with environmental monitoring data, indicate that abandoned military facilities, former training grounds, and military waste disposal sites can represent persistent sources of soil contamination, particularly by PTEs, petroleum hydrocarbons, and other hazardous substances.

Most of these "military brownfields" are a legacy of the Soviet military withdrawal following the collapse of the Eastern Bloc. After the withdrawal of Soviet troops, extensive areas previously used for military purposes were transferred to civilian administration, including local authorities in some countries.

One of the major challenges associated with these former military sites is the limited visibility of their environmental degradation. Many such areas, including former air bases, firing ranges, and ammunition depots, are located in forests, suburban zones, or other areas covered by vegetation. Although these sites may appear environmentally undisturbed, their soils and groundwater can contain localised contamination by volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), potentially toxic elements (PTEs), and petroleum hydrocarbons. In addition, buried unexploded ordnance (UXO) may pose serious safety risks and restrict access, environmental investigations, and future land use.

Spatial planning studies in Poland and Hungary (Szabó et al., 2025) suggest that the presence of abandoned and potentially contaminated brownfields outside densely built-up urban areas may complicate sustainable urban development. In some cases, the high costs of environmental assessment and remediation discourage the redevelopment of these sites, while new investments are directed towards previously undeveloped land. This may contribute to urban sprawl, additional land take, and the loss of valuable agricultural soils.

Sources of information to assess the problem on the local scale

Local administrations generally have information on the location of active and former military training grounds within their municipalities, including sites used for military purposes over the past century. However, assessing the extent of soil degradation in areas currently used by the military can be challenging, as access to these sites is often restricted. The situation is different for former military training grounds that have been decommissioned and transferred to local authorities. In such cases, assessing the degree of soil degradation is generally more feasible, as these areas are usually accessible for environmental investigations.

It is worth noting that not all military areas are severely degraded from an ecological perspective. Some former military training grounds have preserved valuable natural habitats, including grasslands and heathlands, due to long-term restrictions on intensive agricultural activities, urban development, and other forms of human disturbance. Therefore, localised soil degradation in areas subjected to intensive military training should be distinguished from the overall ecological condition of the entire military site.

Furthermore, it is important to consider the spatial variability of soil contamination. Local contamination hotspots frequently occur within military training grounds, particularly in firing

ranges, ammunition detonation sites, military equipment storage areas, and vehicle maintenance facilities. Therefore, soil contamination should not be assumed to be uniformly distributed across the entire site.

For local authorities, historical land-use records, military archives, cadastral maps, aerial photographs, and available environmental monitoring data can provide valuable information for identifying potentially degraded areas within former military sites. These sources can support preliminary environmental assessments and help identify locations requiring more detailed investigations. Particular attention should be paid to former firing ranges, ammunition storage and disposal sites, and vehicle maintenance facilities, where the risk of soil contamination may be relatively high. Such information can support spatial planning, environmental risk assessment, and decisions regarding the safe redevelopment or ecological restoration of former military areas.

Land and soil degradation due to severe acidification

Description the problem and forms of land and soil degradation

Soil acidification is an environmental process characterised by a progressive decrease in soil pH, which, when excessive, represents a major form of chemical soil degradation. A substantial decrease in soil pH, particularly below 5.0, can trigger a series of chemical and biological changes that adversely affect soil fertility, biological activity, and, under certain conditions, physical properties.

Soil acidification contributes to soil degradation through three main mechanisms:

Chemical toxicity and nutrient depletion

When soil becomes strongly acidic, particularly at pH values below 5.0, the solubility and mobility of certain elements, especially aluminium (Al) and manganese (Mn), may increase significantly. Elevated concentrations of soluble aluminium, particularly Al^{3+}, can become toxic to plants, damaging root tips and restricting root growth, thereby reducing water and nutrient uptake. Under strongly acidic conditions, phosphorus (P) availability may also decrease due to its adsorption onto iron (Fe) and aluminium (Al) oxides and hydroxides, as well as precipitation reactions involving these elements. In addition, essential base cations, including calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}), may be progressively leached from the soil profile, resulting in nutrient depletion and reduced soil fertility.

Suppression of soil biological activity

Low soil pH can alter the composition, diversity, and activity of soil microbial communities, often reducing the activity of acid-sensitive microorganisms. Important biological processes, including symbiotic nitrogen fixation and microbial nitrification, may be inhibited under strongly

acidic conditions. Soil acidification can also affect the decomposition of soil organic matter and associated nutrient mineralisation processes, potentially disrupting nutrient cycling and reducing nutrient availability to plants.

Deterioration of soil structure and increased erosion risk

Severe soil acidification may indirectly contribute to the deterioration of soil physical properties, particularly when accompanied by the depletion of exchangeable base cations, reduced biological activity, and changes in soil organic matter dynamics. These processes can affect soil aggregate stability, porosity, and water infiltration, although their effects depend strongly on soil mineralogy, texture, and organic matter content. Furthermore, aluminium and manganese toxicity, combined with nutrient deficiencies, may restrict plant growth and reduce vegetation cover. Consequently, soils with insufficient vegetation protection may become more susceptible to water and wind erosion, leading to the progressive loss of topsoil and further land degradation.

The causes of soil acidification vary, but they can generally be divided into three main categories:

Agricultural Sources

One of the most common causes of agricultural soil acidification is the repeated application of ammonium-based and ammonium-producing nitrogen fertilisers, such as ammonium sulphate and urea. During nitrification, ammonium (NH_4^+) is converted into nitrate (NO_3^-), releasing hydrogen ions (H^+) and contributing to soil acidification, particularly when nitrate is subsequently leached from the soil. Another important factor is the continuous harvesting and removal of crops, hay, and plant residues. During growth, plants take up essential nutrients, including base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). The removal of harvested biomass results in the export of these nutrients from agricultural fields. If these losses are not compensated for by fertilisation, liming, or other soil management practices, the depletion of base cations may contribute to progressive soil acidification. Intensive monoculture farming may also contribute to soil acidification, particularly when combined with excessive nitrogen fertilisation, continuous nutrient removal, and insufficient replenishment of soil nutrients and organic matter.

Industrial Sources

Industrial activities, particularly fossil fuel combustion in power plants, industrial facilities, and other emission sources, release sulphur dioxide (SO_2) and nitrogen oxides (NO_x) into the atmosphere. These compounds can undergo atmospheric chemical reactions, forming sulphuric and nitric acids that are subsequently deposited on soils through wet and dry atmospheric deposition. This process, commonly associated with acid rain, can accelerate soil acidification, promote the leaching of base cations, and contribute to chemical soil degradation.

Natural Processes

In humid temperate and tropical regions, prolonged or intensive rainfall can promote the

leaching of base cations, including calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and sodium (Na^{+}), from the soil profile. Their removal from the soil exchange complex contributes to a progressive increase in soil acidity and the relative dominance of hydrogen (H^{+}) and aluminium (Al^{3+}) ions. Changes in precipitation patterns associated with climate change, including an increase in the frequency or intensity of heavy rainfall events in some regions, may further enhance the leaching of base cations under favourable soil and hydrological conditions, potentially accelerating soil acidification.

The geological parent material also plays an important role in determining natural soil acidity. Soils developed from the weathering of acidic, base-poor rocks, such as granite and certain types of sandstone, often have a low base saturation and limited acid-neutralising capacity. Consequently, these soils may be naturally acidic and particularly susceptible to further acidification.

The scale of the problem in CE region

Soil degradation represents a major environmental challenge in the CE region, with severe soil acidification remaining a significant and long-standing problem. However, its intensity varies considerably depending on local geological conditions, soil properties, and historical agricultural practices. Across the European Union, approximately 10% of agricultural topsoils are classified as acidic (pH < 5.5) (De Vos et al., 2023). However, the extent and severity of soil acidification vary considerably across the CE region, with particularly pronounced problems in certain countries and land-use systems.

Poland: A major hotspot of agricultural soil acidification

Poland is among the European countries most severely affected by agricultural soil acidification. Due to the widespread occurrence of soils developed from post-glacial, base-poor parent materials with limited buffering capacity, approximately 60% of arable soils in Poland require liming. The repeated application of acidifying nitrogen fertilisers, combined with insufficient liming, has contributed to the progressive acidification of agricultural soils and the deterioration of their chemical fertility.

Central European mountain and forest ecosystems

Extensive temperate and mountain forest ecosystems across Germany, Austria, and the Czech Republic have been significantly affected by historical atmospheric acid deposition. During the second half of the 20th century, large parts of Central Europe experienced high levels of acid deposition associated with sulphur dioxide and nitrogen oxide emissions, particularly from coal combustion and heavy industry. Although atmospheric sulphur emissions have declined substantially, the legacy of historical acid deposition persists in many forest soils. In some areas,

deeper mineral soil horizons remain strongly acidic, with continued depletion and leaching of essential base cations, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}).

Nutrient Imbalances and Intensive agricultural land use

Approximately 74% of European agricultural land is affected by nutrient imbalances (Akca et al., 2024). Although nutrient imbalances do not necessarily indicate soil acidification, intensive agricultural practices may contribute to this process in certain areas of Hungary, Slovakia, and northern Italy.

Sources of information to assess the problem on the local scale

It is important to distinguish between naturally acidic soils and soils affected by anthropogenic acidification. Low soil pH does not necessarily indicate soil degradation, as many forest soils and soils developed from acidic parent materials are naturally acidic. For local administration, the assessment of soil acidification as a degradation process should therefore consider not only soil pH but also soil type, parent material, land-use history, base saturation, and the potential impacts on soil functions and vegetation.

Local administrations can assess the extent of soil acidification, mostly related to agricultural soil within their municipalities by collecting data from local agricultural databases and other local and regional databases that provide information on the spatial distribution and monitoring of soil acidity. They can also obtain relevant information from individual farmers who routinely submit soil samples to accredited laboratories for the determination of soil pH, macronutrient availability, and liming requirements. Subsidised soil testing programmes are also supported by many municipalities.

If the available data lack sufficient spatial resolution, local administrations can take proactive measures to develop their own detailed soil acidity databases. Municipal councils may adopt resolutions to co-finance or subsidise soil sampling and laboratory analyses for local farmers and landowners. Soil samples can be collected from the topsoil by landowners or trained personnel using hand-held soil sampling probes. The samples can then be collected and coordinated by the local administration and submitted to accredited agricultural or environmental laboratories for analysis. At a relatively low cost per sample, such coordinated soil testing programmes can provide local administrations with valuable data for developing detailed maps of soil acidity and liming requirements across their municipalities. These maps can support agricultural soil management, identify areas at risk of progressive acidification, and help prioritise measures aimed at maintaining or restoring soil fertility.

Land and soil degradation due to alkalisation, sodification

and salinisation

Description the problem and forms of land and soil degradation

Soil and land degradation caused by salinisation, sodification, and alkalisation represents a significant form of chemical and physical degradation. These processes alter soil chemical properties, may adversely affect soil structure, and can severely limit the capacity of soils to support plant growth. In extreme cases, they may lead to substantial vegetation loss, reduced biodiversity, and, in susceptible dryland regions, desertification. Salinisation and sodification may occur simultaneously, particularly in arid, semi-arid, and coastal environments, although they affect soils through different mechanisms.

Degradation by salinisation (accumulation of soluble salts)

Soil salinisation occurs when water-soluble salts, including chlorides, sulphates, and bicarbonates of sodium, calcium, and magnesium, accumulate in the soil profile, particularly within the root zone. Excessive salt accumulation can cause soil degradation through several mechanisms:

Osmotic Stress ("Physiological Drought"): High concentrations of dissolved salts reduce the osmotic potential of soil water, making it more difficult for plant roots to absorb water. As a result, plants may experience water stress even when sufficient moisture is present in the soil.

Ion Toxicity: Excessive uptake and accumulation of certain ions, particularly sodium (Na^+) and chloride (Cl^-), can cause toxic effects in sensitive plants, disrupting physiological and metabolic processes, reducing crop yields, and potentially leading to vegetation decline.

Vegetation Loss and Increased Erosion Risk: Severe salinity may inhibit plant growth and reduce vegetation cover, leaving the soil surface more exposed to wind and water erosion. The resulting loss of protective vegetation can accelerate land degradation.

Surface Salt Crust Formation: Under conditions of high evaporation and insufficient leaching, soluble salts may accumulate and crystallise at the soil surface, forming visible white or grey salt crusts. These crusts can interfere with seed germination and plant establishment and, depending on their composition and structure, may affect surface water infiltration.

Degradation by sodification and alkalisation (exchangeable sodium accumulation and elevated soil pH)

Soil sodification occurs when the proportion of exchangeable sodium (Na^+) in the soil exchange complex increases relative to other exchangeable cations, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}). Sodification is frequently associated with elevated soil pH, although sodicity and alkalinity are distinct soil chemical properties. High exchangeable sodium levels, particularly under conditions of low electrolyte concentration in the soil solution, can cause severe deterioration of soil physical properties through the following mechanisms:

Clay dispersion: High proportions of exchangeable sodium can promote the swelling and dispersion of clay particles, particularly when the concentration of dissolved salts in soil water is low. This reduces the stability of soil aggregates.

Deterioration of soil structure: Clay swelling and dispersion can disrupt soil aggregates and alter soil pore distribution, resulting in reduced structural stability and the formation of dense, poorly structured soil layers.

Reduced permeability and water infiltration: Dispersed clay particles may block soil pores, reducing hydraulic conductivity and water infiltration. This can lead to surface crusting, waterlogging, and poor internal drainage. Upon drying, severely sodic soils may become extremely hard, restricting root penetration and seedling emergence.

Coastal soil degradation (seawater intrusion and salt accumulation)

In coastal regions, soil salinisation can be intensified by the interaction between marine and terrestrial hydrological processes, particularly in low-lying areas and regions affected by sea-level rise.

Seawater intrusion and coastal flooding: Sea-level rise, storm surges, and coastal flooding can introduce saline water into agricultural soils and freshwater systems. Seawater intrusion into coastal aquifers may also increase groundwater salinity, creating a long-term risk of soil salinisation where saline groundwater interacts with the root zone.

Capillary rise of saline groundwater: In coastal areas with shallow saline groundwater tables, capillary rise can transport dissolved salts upwards through the soil profile. Under conditions of high evaporation, water is lost from the soil surface while salts remain and accumulate in the upper soil horizons. Repeated cycles of capillary rise and evaporation may progressively increase topsoil salinity, particularly where drainage is insufficient.

The main sources of soil salinisation, sodification, and alkalisation can be divided into two broad categories: natural sources, associated with geological, geographical, and climatic conditions, and anthropogenic sources, resulting from human activities and inappropriate land management practices.

The main factors contributing to these processes are described below.

Natural Sources

Natural soil salinisation sodification, and alkalisation may develop over long periods as a result of geological, climatic, and hydrological conditions, particularly in arid, semi-arid, and coastal environments.

Weathering of parent material: The chemical weathering of rocks and minerals, including feldspars and other sodium-, calcium-, and magnesium-bearing minerals, releases dissolved ions into soil and groundwater. Depending on local geological and hydrological conditions, these ions may contribute to the accumulation of soluble salts and influence soil alkalinity.

Atmospheric deposition (sea spray and wind-blown salts): Wind can transport sea-salt aerosols from coastal areas and saline dust from dry lake beds and other salt-affected surfaces. These materials are subsequently deposited on soils through wet deposition (rain and snow) or dry atmospheric deposition, contributing to salt accumulation.

Low rainfall and high evaporation: In arid and semi-arid climates, limited rainfall reduces the natural leaching of soluble salts from the soil profile. At the same time, high evaporation rates can promote the upward movement of saline soil water through capillary rise, resulting in salt accumulation in the upper soil horizons and at the soil surface.

Topography and poor natural drainage: Low-lying areas, enclosed basins, and topographic depressions may accumulate surface runoff and dissolved salts transported from surrounding uplands. Where natural drainage is restricted, evaporation and insufficient leaching can promote the progressive accumulation of salts in soils.

Anthropogenic Sources

Human activities can significantly accelerate soil salinisation, sodification, and alkalisation, potentially reducing soil fertility, agricultural productivity, and ecosystem functions over relatively short periods.

Irrigation with saline or poor-quality water: The repeated use of irrigation water containing elevated concentrations of dissolved salts can progressively increase soil salinity, particularly where irrigation is not accompanied by sufficient leaching and adequate drainage. The risk of soil sodification also depends on the sodium concentration relative to calcium and magnesium in irrigation water.

Inadequate drainage and waterlogging: Excessive irrigation or prolonged waterlogging under conditions of insufficient drainage may cause the groundwater table to rise towards the soil surface. Where groundwater is saline, capillary rise can transport dissolved salts into the root zone and upper soil horizons. Subsequent evaporation leaves these salts behind, leading to their progressive accumulation.

Overexploitation of groundwater: Excessive extraction of freshwater from coastal aquifers can lower groundwater levels and alter hydraulic gradients, promoting seawater intrusion into freshwater aquifers. The resulting increase in groundwater salinity may contribute to soil salinisation where saline groundwater reaches or influences the root zone, particularly under conditions of shallow groundwater and high evaporation.

Deforestation and land clearing: The removal of deep-rooted native vegetation can reduce evapotranspiration and increase groundwater recharge, potentially causing the groundwater table to rise. In landscapes containing naturally saline groundwater or salt-bearing geological deposits, this process may transport dissolved salts towards the soil surface and contribute to secondary salinisation.

Mining activities and industrial effluents: Mineral extraction, coal mining, and oil and gas production can generate or mobilise saline waters, including mine drainage and produced water, which may contain high concentrations of dissolved salts. Accidental leaks, inadequate storage, uncontrolled discharge, or seepage from waste disposal facilities can introduce these saline waters into surrounding soils, surface waters, and groundwater. Such contamination may lead to persistent soil salinisation and adversely affect agricultural land and natural ecosystems.

Application of road de-icing salts: The widespread use of de-icing salts, particularly sodium chloride (NaCl), on roads and motorways during winter can cause seasonal increases in soil salinity in adjacent areas. During snowmelt and rainfall, dissolved salts are transported into roadside soils through runoff and infiltration. Elevated concentrations of sodium (Na^+) and chloride (Cl^-) can cause osmotic stress and ion toxicity in roadside vegetation. Under certain soil conditions, sodium accumulation in the soil exchange complex may also promote clay dispersion, deterioration of soil structure, and reduced water infiltration. However, soil alkalisation is not an inevitable consequence of sodium chloride application and depends on soil chemistry and buffering conditions.

Cement and ceramic Industries (alkaline dust deposition): Cement production and certain ceramic manufacturing processes can contribute to localised soil alkalisation through the emission and atmospheric deposition of alkaline particulate matter. Cement kiln dust may contain calcium carbonate ($CaCO_3$), calcium oxide (CaO), calcium hydroxide [$Ca(OH)_2$], and compounds containing potassium and sodium. Following deposition on surrounding soils, reactive alkaline components, particularly calcium oxide and calcium hydroxide, can react with soil moisture and increase soil pH. In areas exposed to substantial alkaline dust deposition, these processes may alter soil chemical properties and reduce the availability of certain nutrients, including iron, manganese, and phosphorus. The magnitude of these effects depends on dust composition, deposition rates, soil buffering capacity, and environmental conditions. In addition, soluble salts present in industrial dust and waste materials, including sodium and potassium chlorides and sulphates, may contribute to increased soil electrical conductivity and localised salinisation.

The chemical industry, particularly soda ash (sodium carbonate, Na_2CO_3) production, can be a significant anthropogenic source of localised soil alkalisation and salinisation. These processes are mainly associated with the release of alkaline and saline industrial effluents during production and the leaching of soluble salts from industrial waste disposal sites. The main raw materials used in soda ash production are brine (a concentrated aqueous solution of sodium chloride, NaCl) and limestone ($CaCO_3$). The traditional Solvay process generates large volumes of liquid and semi-liquid waste, including distillation residues, which have historically been discharged into settling ponds and industrial waste disposal facilities. In some regions, these disposal sites are locally known as "white seas" because of the characteristic appearance of the accumulated waste materials.

The scale of the problem in CE region

In the Central European (CE) region, soil and water salinisation, sodification, and alkalisation represent important environmental challenges, particularly in areas affected by natural salt accumulation, intensive industrial activities, and changing climatic conditions. Although Central Europe is generally less affected by climate-driven soil salinisation than the arid and semi-arid regions of Southern Europe, several areas within the region are particularly vulnerable to these processes (European Comission, 2026). Their occurrence and environmental significance can be considered in three main contexts:

Natural salt accumulation: The Pannonian Basin and Hungary

Hungary represents one of the most characteristic examples of naturally occurring saline and sodic soils in Central Europe. Salt Accumulation in the Pannonian Basin: The Pannonian Basin contains extensive low-lying areas where geological conditions, groundwater chemistry, restricted drainage, and climatic factors favour the accumulation of soluble salts. Groundwater and soil solutions may contain elevated concentrations of sodium, calcium, magnesium, bicarbonates, carbonates, and other dissolved ions, depending on local geological and hydrological conditions. Soil salinisation, sodification, and alkalisation (Solonchaks and Solonetz) is also the problem in areas with shallow saline groundwater, capillary rise and evaporation can promote the accumulation of soluble salts in the upper soil horizons. Where sodium dominates the soil exchange complex, sodification may lead to clay dispersion, deterioration of soil structure, and reduced water infiltration. Some affected soils exhibit strongly alkaline conditions, with pH values exceeding 8.5 or even 9.0. These properties can substantially restrict agricultural productivity and influence the composition of natural vegetation. Recently published studies have identified Hungary and parts of Romania as emerging hotspots of increasing freshwater salinity (Crabot et al., 2026).

Anthropogenic salinisation: Poland and Germany

In the northern and central parts of the CE region, anthropogenic salinisation is particularly associated with mining, industrial activities, and the discharge of saline wastewater. In Poland, the Oder and Vistula river basins are affected by discharges of saline mine waters, particularly from coal mining areas. Similar pressures may occur in industrial and mining regions of Germany, although their extent and intensity vary between river basins. Elevated concentrations of dissolved salts, particularly chlorides and sulphates, can increase river-water salinity and adversely affect freshwater ecosystems. The severity of these effects depends on the volume and chemical composition of discharges, river flow conditions, and the capacity of receiving waters to dilute pollutants.

Chemical and Soda Industries: Historical and current soda ash production, particularly using the Solvay process, has generated substantial quantities of saline and alkaline waste. In some

industrial regions of Poland and Germany, historical waste disposal facilities, including settling ponds and deposits of soda production residues, have contributed to localised soil and groundwater salinisation and alkalisation. These facilities, sometimes referred to as "white seas", may contain highly alkaline materials and substantial concentrations of soluble salts. Leachate migration from inadequately protected disposal sites can affect surrounding soils, groundwater, and surface waters.

Climate change as an accelerating factor

Climate change may intensify soil and water salinisation in parts of CE through rising temperatures, more frequent heatwaves, prolonged droughts, and changes in precipitation patterns. Higher temperatures and prolonged dry periods may increase soil evaporation and reduce the natural leaching of soluble salts. In areas with shallow saline groundwater, enhanced capillary rise and evaporation can promote salt accumulation in the root zone and upper soil horizons. The interaction between existing industrial contamination, naturally saline geological environments, and climate-related hydrological changes may increase the vulnerability of certain Central European regions to soil and water salinisation. These combined pressures should be considered in regional environmental monitoring, agricultural soil management, and land-use planning.

Sources of information to assess the problem on the local scale

Outside specific regions, such as the Pannonian Basin, soil salinisation, sodification, and alkalisation in Central Europe tend to occur primarily at the local scale. A practical first step for local administrations is to prepare an inventory of potential salinity and alkalinity sources, including industrial waste disposal sites, saline mine water discharges, road de-icing salt storage facilities, and areas affected by saline groundwater. This inventory can then be used to design a targeted and cost-effective soil and water monitoring programme.

To effectively assess these processes at the municipal level, local administrations should not rely solely on general national maps and regional-scale databases. They should combine information on existing and historical industrial sources located within their municipalities or neighbouring municipalities with available data from agricultural soil testing laboratories and regional institutions responsible for soil monitoring. These institutions may possess extensive long-term datasets on topsoil chemical properties, compiled from soil analyses carried out for farmers on a voluntary basis or under specific regulatory requirements. Remote sensing data and targeted local soil monitoring can provide additional information for identifying potentially affected areas and assessing the spatial extent of soil degradation. Relatively simple and inexpensive measurements of electrical conductivity (EC) in soil and water can also provide valuable preliminary information on salinity levels. However, the assessment of soil sodicity and alkalinity requires additional

chemical parameters, particularly soil pH and indicators of exchangeable sodium, such as the exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR). Combining these complementary sources of information can help local administrations identify areas at risk, prioritise detailed investigations, and support appropriate land management decisions.

Land and soil degradation due long-term inappropriate agricultural practices

Description the problem and forms of land and soil degradation

Long-term inappropriate agricultural practices can cause land and soil degradation by adversely affecting soil physical structure, chemical properties, and biological functions. When intensive agricultural practices exceed the natural capacity of soils to maintain their functions, they may initiate a series of interconnected degradation processes, progressively reducing soil fertility and agricultural productivity and, in severe cases, leading to declining crop yields. Attempts to compensate for reduced productivity through increased fertiliser application or more intensive tillage may further aggravate soil degradation if the underlying causes are not addressed. This can create a negative feedback loop in which declining soil quality increases the vulnerability of agricultural systems to extreme weather events, including droughts and heavy rainfall, ultimately threatening agricultural productivity and regional food security.

The main mechanisms through which inappropriate agricultural practices contribute to long-term soil and land degradation include:

Physical degradation of soil structure

Soil compaction and plough pan formation: Repeated use of heavy agricultural machinery, particularly under excessively wet soil conditions, can cause soil compaction and reduce soil porosity. Repeated tillage at a similar depth may also contribute to the formation of a dense, compacted subsurface layer, commonly known as a plough pan. Such layers restrict root penetration, reduce water infiltration and internal drainage, and limit soil aeration, adversely affecting plant growth.

Accelerated wind and water erosion: Intensive tillage can disrupt soil aggregates and reduce their stability, making soil particles more susceptible to detachment and transport. The removal of protective vegetation cover and crop residues leaves the soil surface exposed to rainfall impact, surface runoff, and wind erosion. Over time, these processes can result in substantial losses of fertile topsoil and associated nutrients and organic matter.

Reduced soil water retention and increased drought vulnerability: Long-term deterioration of soil structure and the loss of soil organic matter can reduce the capacity of soils to retain and

supply water to plants. Poor soil aggregation, compaction, and reduced infiltration may increase surface runoff while limiting water storage within the root zone. These processes can make agricultural soils more vulnerable to prolonged dry periods and increase the risk of crop water stress, particularly under changing climatic conditions.

Chemical degradation

Nutrient depletion: Continuous cultivation of the same crop or a limited number of crops, particularly without adequate nutrient replenishment and appropriate crop rotation, may lead to the progressive depletion of certain essential nutrients. Repeated nutrient removal through harvesting, combined with insufficient fertilisation or organic amendments, can reduce soil fertility and agricultural productivity. The severity of nutrient depletion depends on crop requirements, soil properties, and nutrient management practices.

Salinisation and sodification: Excessive irrigation, the use of saline or sodium-rich irrigation water, and inadequate drainage can promote the accumulation of soluble salts and exchangeable sodium in soils. In areas with shallow saline groundwater, capillary rise and evaporation may increase salt concentrations in the root zone. Salinisation can restrict plant water uptake and cause ion toxicity, while sodification may promote clay dispersion, deterioration of soil structure, and reduced water infiltration.

Soil acidification and chemical contamination: Long-term application of certain nitrogen fertilisers, particularly ammonium-based fertilisers, can contribute to soil acidification through nitrification and associated processes of proton generation and base-cation leaching. Inadequate nutrient management may further accelerate soil acidification and reduce the availability of essential nutrients while increasing the mobility of certain potentially toxic elements. In addition, excessive or inappropriate use of some agricultural chemicals may introduce persistent residues or potentially toxic elements into soils, with possible adverse effects on soil organisms and, under suitable transport conditions, groundwater quality.

Biological degradation

Loss of soil organic matter (SOM): Repeated intensive tillage can accelerate the decomposition of soil organic matter by disrupting soil aggregates and increasing the exposure of previously protected organic material to microbial decomposition. When organic matter inputs from crop residues, roots, and organic amendments are insufficient to compensate for these losses, soil organic carbon stocks may progressively decline. Reduced soil organic matter content can adversely affect soil aggregate stability, water-holding capacity, nutrient retention, and biological activity.

Decline in soil biodiversity and biological functions: Intensive tillage, limited crop diversity, reduced organic matter inputs, and inappropriate application of pesticides or other agricultural chemicals can negatively affect soil organisms and biological processes. Earthworms, mycorrhizal fungi, and various groups of soil microorganisms may decline in abundance or diversity, depending

on the intensity and duration of agricultural pressures. Such changes can disrupt nutrient cycling, soil aggregation, organic matter decomposition, and other essential ecosystem functions, further reducing soil resilience and agricultural productivity.

The problem on the CE scale

In the CE region, soil degradation resulting from long-term intensive and inappropriate agricultural practices represents a significant environmental, social, and land management challenge. The region is characterised by diverse topographical conditions, ranging from extensive agricultural plains to hilly landscapes and Alpine mountain areas, as well as different historical patterns of agricultural development. In several CE countries, particularly those formerly belonging to the Eastern Bloc, agricultural intensification and land consolidation during the second half of the twentieth century substantially transformed traditional agricultural landscapes.

In countries such as Czechia, Slovakia, Hungary, Eastern Germany and Poland, the post-war period was characterised by varying forms and degrees of agricultural collectivisation, state-controlled farming, and land consolidation. In many areas, smaller agricultural fields were combined into large, continuous plots to facilitate mechanised cultivation. This transformation was frequently accompanied by the removal of hedgerows, field boundaries, trees, and other landscape elements that had previously contributed to reducing wind and water erosion, supporting biodiversity, and regulating surface runoff.

More recently, climate change has intensified some of these environmental pressures. Central Europe is experiencing rising temperatures, more frequent or prolonged periods of drought in many areas, and an increased risk of intense rainfall events. Where agricultural soils are compacted, poorly structured, or depleted in organic matter, heavy rainfall may generate substantial surface runoff, local flooding, and accelerated soil erosion. The combined effects of historical land-use changes, intensive agricultural practices, and climate-related pressures can therefore increase the vulnerability of agricultural soils to further degradation.

Although the intensity and spatial distribution of soil degradation processes caused by long-term inappropriate agricultural practices vary considerably between regions, the following processes are particularly important:

Loss of soil organic matter (SOM) and soil organic carbon (SOC).

Soil and subsoil compaction caused by repeated use of heavy agricultural machinery.

Accelerated water and wind erosion caused by intensive tillage. Water erosion is particularly important in sloping agricultural landscapes, including parts of Czechia, southern Poland, and other hilly regions of Central Europe. Wind erosion may also affect extensive agricultural plains, particularly in the Pannonian Basin, where exposed soils are vulnerable during dry and windy

periods. Both processes can lead to the loss of fertile topsoil, soil organic matter, and nutrients, reducing long-term agricultural productivity.

Nutrient imbalances and chemical contamination as a result of long-term monoculture, inadequate crop rotation, unbalanced fertilisation, and insufficient nutrient replenishment can contribute to nutrient depletion or imbalances in agricultural soils. Conversely, excessive or inappropriate fertiliser application may lead to nutrient accumulation, particularly phosphorus and nitrogen compounds, and increase the risk of nutrient losses to surface waters and groundwater. The repeated use of certain pesticides and other agricultural chemicals may also result in the accumulation of persistent residues or potentially toxic elements in soils, depending on their composition, application rates, and environmental persistence. These processes can adversely affect soil quality, biological functions, and surrounding ecosystems.

Sources of information to assess the problem on the local scale

Because soil degradation caused by long-term inappropriate land use develops gradually, local administrations need to adopt a comprehensive approach to collecting data that can support decision-making. Long-term data collected from farmers, agricultural organizations, and laboratories conducting soil analyses are particularly important. Information on persistent declines in crop yields that cannot be explained by short-term weather conditions is also valuable. A comprehensive assessment of agricultural practices and farming methods used within the municipality is also necessary. While identifying the problem and assessing its scale within a municipality is relatively straightforward, determining its underlying causes requires more detailed analysis and specialized knowledge. This may involve cooperation with scientists, commissioning external expert assessments, and monitoring changes over time.

Land and soil degradation due to the wind and water erosion

Description the problem and forms of land and soil degradation

Wind and water erosion degrade land and soil by stripping away the nutrient-rich topsoil, destroying soil structure, and reducing the land's ability to support plant life.

Wind erosion

Wind erosion happens when strong air currents blow across dry, exposed, and sparsely vegetated land. The results of wind erosion are as follow:

• Loss of fertile soil particles: Wind selectively removes fine, nutrient-rich soil particles, such as silt and clay, together with organic matter (humus), leaving behind coarser, less fertile

material, such as sand and gravel.

• Reduced water retention: The loss of organic matter and fine soil particles significantly reduces the soil's capacity to retain water, increasing its vulnerability to drought and further degradation.

• Abrasion and burial: Wind-blown dust and sand particles can damage growing plants and reduce vegetation cover. Deposited material may also accumulate in certain areas, covering agricultural land, blocking drainage channels, or damaging infrastructure.

• Root exposure and vegetation loss: The removal of surface soil particles by wind (deflation) gradually exposes plant roots, weakening or destroying vegetation and increasing the risk of further soil erosion.

Water erosion

Water erosion occurs when rainfall, surface runoff, or flooding detaches and transports soil particles.

• Splash erosion: Heavy raindrops strike exposed soil, breaking down soil aggregates and displacing individual particles. This process can contribute to the formation of surface crusts that reduce water infiltration into the soil.

• Sheet and rill erosion: Water flowing across the soil surface as a thin layer (sheet erosion) or concentrating in small channels (rill erosion) removes nutrient-rich topsoil containing organic matter and essential plant nutrients.

• Gully erosion: If left unchecked, small erosion channels may develop into deeper and wider gullies, dividing agricultural fields and making cultivation difficult or, in severe cases, impossible.

• Loss of soil depth and structure: Continuous removal of topsoil reduces the depth of the fertile soil layer, limits root development, and may negatively affect soil structure and water infiltration.

• Off-site sedimentation: Eroded soil particles are transported into nearby rivers, lakes, and drainage channels, contributing to sediment accumulation, deterioration of aquatic habitats, and the transport of nutrients and potentially harmful contaminants.

The scale of the problem in CE region

According to Eurostat and European Commission Joint Research Centre (JRC) data, the average soil loss across agricultural land in the EU sits at roughly 3.07 tonnes per hectare per year (t/ha/yr) (Panagos et al., 2021). The main factors contributing to soil erosion are:

Unsustainable agricultural practices: Intensive tillage, the removal of natural landscape barriers (such as hedgerows), inappropriate fertilization practices, and leaving soil bare during winter can accelerate soil erosion. Intensive soil cultivation and insufficient organic matter inputs

can also reduce soil organic matter content, weakening soil structure and increasing its susceptibility to erosion. In Central Europe, this problem is particularly significant in countries where agricultural collectivization was introduced during the second half of the 20th century, leading to the consolidation of small agricultural plots into large fields and the removal of natural landscape barriers. This historical process has contributed to increased erosion risk, particularly in the Czech Republic, Slovakia, Hungary, eastern Germany, and parts of northern and western Poland. Similar problems occur in northern Italy, especially in the Po Valley, covering regions such as Lombardy, Emilia-Romagna, Piedmont, and Veneto. However, in this region, the development of large-scale intensive agriculture was not driven by collectivization but by a long history of land reclamation and agricultural improvement, substantial capital investment, and strong integration with the agri-food industry.

Impact of climate change: Increasingly frequent periods of prolonged drought followed by intense rainfall can accelerate soil erosion. During droughts, reduced vegetation cover and changes in soil surface conditions may increase susceptibility to erosion, while subsequent heavy rainfall can generate intense surface runoff and significant soil loss. This problem affects the entire Central European region, although its severity varies depending on local climatic conditions, soil properties, land use, and topography.

Topography: Sloping terrain increases the velocity and erosive power of surface runoff, making mountainous and hilly areas particularly vulnerable to water erosion. In Central Europe, this problem is especially relevant in the Alpine and Carpathian regions, as well as other upland areas. Significant water erosion risks occur in parts of Italy and Slovenia and in mountainous regions of other Central European countries, particularly where steep slopes are combined with intensive rainfall and inadequate soil protection.

Sources of information to assess the problem on the local scale

Local administrations can obtain information on soil and land degradation within their municipalities from publicly available European and national geological and agricultural databases, as well as from local technical assessments. Although these databases often provide information at a regional scale, they can be useful for identifying areas potentially affected by soil erosion and assessing the general scale of the problem within a municipality. The effects of water erosion are particularly visible in areas affected by flooding or following intense rainfall events. Wind erosion, on the other hand, is most evident in large, exposed agricultural fields, particularly where soils are dry, loose, and lack protective vegetation cover. A more detailed assessment of soil erosion at the individual plot level may require specialized field surveys and high-resolution spatial data, supported by digital modelling tools that are not always readily available to local administrations.

Land and soil degradation due to the soil sealing or compaction

Description the problem and forms of land and soil degradation

Soil sealing and compaction contribute to land and soil degradation by severely impairing the physical, biological, and hydrological functions of soil.

Soil sealing

Soil sealing occurs when the natural soil surface is covered with impermeable materials such as concrete, asphalt, buildings, or paving stones.

Sealing restricts or prevents the exchange of water and gases between the soil and the atmosphere, disrupting natural soil processes.

Impermeable surfaces prevent rainwater from infiltrating the soil, increasing surface runoff, the risk of local flooding, and reducing the soil's natural water filtration capacity.

Soil sealing significantly reduces soil biological activity and may contribute to the loss of soil organic carbon (SOC), particularly when the original topsoil is removed or disturbed during construction.

Concrete and asphalt surfaces absorb and retain solar heat, while the loss of vegetation reduces cooling through evapotranspiration, contributing to higher local temperatures and the urban heat island effect.

Soil compaction

Soil compaction occurs when pressure from heavy machinery, repeated agricultural operations, or intensive livestock trampling compresses the soil.

Mechanical pressure forces soil particles closer together, reducing pore space, particularly large pores, and potentially damaging soil structure.

Compacted soil restricts root penetration and reduces soil aeration, limiting oxygen availability for plant roots and soil organisms.

Reduced soil porosity and permeability limit water infiltration and drainage, increasing the risk of waterlogging during wet periods and restricting water availability to plants during dry periods.

Reduced water infiltration increases surface runoff, which can accelerate the removal of topsoil and intensify water erosion, particularly on sloping agricultural land.

The scale of the problem in CE region

Soil sealing

Soil sealing is recognized as an important environmental challenge within the Central Europe area, particularly in large metropolitan areas, industrial regions, and expanding suburban zones.

Urban development and infrastructure expansion: Major cities and metropolitan areas, such as Budapest, Bratislava, Prague, Kraków, Warsaw, and Milan (Po Valley), are experiencing increasing pressure from urban development and infrastructure expansion, resulting in the sealing of natural and agricultural soils. The conversion of permeable land into built-up areas and transport infrastructure reduces water infiltration, contributes to the urban heat island effect, and increases pressure on drainage systems during intense rainfall events. Among Central European countries, Austria faces significant challenges related to land take and soil sealing. In many Austrian municipalities, these processes are considered important environmental and spatial planning issues, particularly where infrastructure expansion exceeds the actual needs associated with population growth. However, soil sealing is not limited to large cities. Smaller towns and rural municipalities are also affected by the expansion of residential areas, roads, industrial facilities, and other infrastructure. In addition, unpaved public spaces, construction sites, and frequently used access roads may be particularly vulnerable to soil compaction. These processes demonstrate that physical soil degradation is a widespread concern across both urban and rural areas of Central Europe.

Soil compaction

Soil compaction is one of the major forms of physical soil degradation affecting agricultural land and managed forests in Central Europe. The widespread use of heavy agricultural machinery, including tractors and harvesting equipment, increases the risk of soil compaction, particularly when operations are carried out under unfavourable soil moisture conditions.

This problem is especially relevant in intensively cultivated agricultural regions, such as the Po Valley in Italy and the Hungarian Plain. The use of heavy machinery on moist or wet soils can cause severe subsoil compaction, reducing soil porosity, restricting root development, and negatively affecting crop yields. Soil compaction is also an important problem in forestry. In Central European countries with extensive forest management activities, particularly Slovakia, Austria, and the Czech Republic, heavy logging machinery can cause substantial changes in soil structure. Repeated movement of harvesters and other forestry equipment along extraction routes may increase soil bulk density, create deep wheel ruts, reduce water infiltration, and limit root growth and natural forest regeneration. The severity of these effects depends on soil type, moisture conditions, machinery weight, and the intensity of forest operations.

Sources of information to assess the problem on the local scale

In the case of soil sealing, assessing the scale of the problem is relatively straightforward.

Local administrations generally have access to information on the location of large sealed areas, including public spaces, private properties, industrial sites, infrastructure developments, and large warehouse and commercial facilities. In the case of private properties, additional information can be obtained through inspections carried out by authorized municipal services, where permitted by national legislation. Satellite imagery, such as data from the Sentinel programme, and high-resolution images provided by commercial services can also be used to identify and map sealed surfaces. Remote sensing products showing the extent of impervious surface areas (ISA) are particularly useful for identifying areas where water infiltration is significantly restricted or prevented. More advanced Geographic Information System (GIS) tools are also becoming increasingly available to local administrations, supporting the mapping and monitoring of soil sealing. National orthophotomaps and cadastral data can also serve as primary sources of information. In many cases, these data may be more readily available and useful to local administrations than conducting independent analyses of satellite imagery.

Assessing the degree of soil compaction is somewhat more challenging, as compaction affects the soil structure below the surface and is not always directly visible. Reliable assessment generally requires direct field measurements, but useful preliminary information can also be obtained from indirect indicators, such as:

Assessment of soil susceptibility to compaction: Existing soil and agricultural maps, supported by GIS analyses, can help identify areas potentially vulnerable to soil compaction. Soils with a high proportion of fine particles, particularly clay and silt, may be more susceptible to compaction, especially under wet conditions.

Identification of areas with standing water: Aerial and satellite imagery acquired in spring or following heavy rainfall can help identify agricultural fields where water remains on the surface for extended periods. Such areas may indicate reduced soil permeability caused by compacted subsurface layers, including plough pans. However, prolonged waterlogging may also result from poor drainage, soil texture, or local topographic conditions.

Observation of crop growth patterns: Uneven crop growth, reduced plant development, and persistent areas of poor vegetation cover may indicate soil compaction, particularly where these patterns coincide with repeated machinery traffic. Such observations can be supported by satellite imagery and vegetation indices, although other causes of poor crop growth should also be considered.

State of the knowledge on the soil degradation by local administration of different CE regions

The survey conducted within the framework of the PoLaRecCE project covered six Central European (CE) countries and seven regions. The questionnaire was designed to assess the extent of the 18 forms of land and soil degradation described above at the local (municipal) level. The questionnaire, developed jointly by the project partners, was distributed to all municipalities in seven CE regions: Liguria and Emilia-Romagna (Italy), Eastern Slovenia (Slovenia), Carinthia (Austria), Békés County (Hungary), and Silesian Province (Poland), as well as to three municipalities in eastern Croatia. The following summary is based on 200 responses.

The survey aimed to provide a regional overview of land and soil degradation across the participating Central European regions. Its main objectives were to:

- identify the extent and nature of soil contamination and degradation at the local (municipal) level;
- highlight region-specific patterns and cross-regional trends;
- collect data for the development of a Central European database of degraded land;
- assess the level of knowledge and awareness of local administrations regarding land and soil degradation within their municipalities.

The first, and perhaps most important, conclusion drawn from the survey is the surprisingly low level of awareness of soil degradation among local administrations, regardless of the country or region surveyed. Many municipalities demonstrated only limited awareness of the threats associated with various forms of land and soil degradation, such as contamination from urban and industrial dust deposition, soil erosion, and degradation resulting from long-term inappropriate agricultural practices. In some cases, the responses underestimated or even denied the existence of problems that are well documented at the regional or national level and are also widely recognized by local residents.

The results of the survey conducted within the framework of the PoLaRecCE project have revealed a widespread problem affecting local administrations. The limited awareness among municipal officials of different forms and degrees of soil degradation and chemical contamination may be attributed to several systemic and structural barriers:

The Invisibility of the problem ("Hidden" Contamination)

Unlike air pollution (e.g., smog and unpleasant odours) or water pollution (e.g., visible water discolouration and fish kills), many forms of soil degradation and chemical contamination are not readily visible to the naked eye. Soil heavily contaminated with PTEs, including heavy metals, may appear completely healthy to municipal officials or farmers, and crops growing on it may develop normally, even if they accumulate harmful substances. The absence of clear visual indicators means that soil degradation may receive less attention than more visible environmental problems and consequently become a lower priority for local administrations.

Fragmentation of environmental databases and limited data integration

Although data on soil contamination are available from various sources, including geological institutes, environmental protection agencies, and European monitoring programmes such as LUCAS Soil, they are often scattered across different national and European databases. Local administrations may not have these datasets integrated into their municipal Geographic Information Systems (GIS). Moreover, municipal officials may be unaware of the availability of existing geochemical background maps, historical contamination registers, and other publicly accessible environmental datasets that could support local land management decisions.

Lack of specialized staff in local administrations

In small and medium-sized municipalities, particularly rural and urban-rural ones, environmental protection departments often have limited financial and human resources. In some cases, one or two officials are responsible for a wide range of tasks, including waste management, tree removal permits, asbestos management, heating system replacement subsidies, and reports of illegal waste dumping. Under such circumstances, local administrations may lack the time, resources, and specialized knowledge in soil science, agronomy, and geochemistry needed to assess the extent and severity of land and soil degradation.

Gaps in legal requirements and limited enforcement

For many years, EU environmental legislation placed greater emphasis on water and air protection than on comprehensive soil monitoring and protection. The adoption of the EU Soil Monitoring Law (Directive (EU) 2025/2360) represents an important step towards addressing this imbalance. However, the practical implementation of its provisions will depend on their transposition into national legislation and the establishment of appropriate monitoring and reporting systems. Existing national regulations may require soil investigations in specific circumstances, such as changes in land use, redevelopment of contaminated sites, or suspected environmental damage. However, the gradual deterioration of agricultural soils, including declining fertility and the accumulation of chemical contaminants, may not always trigger systematic monitoring at the municipal level. As a result, local administrations may lack clear procedures, resources, or institutional incentives to identify and assess these processes at an early stage.

Fear of economic consequences (The "Contamination Taboo")

- Officially acknowledging serious soil contamination or degradation within a municipality may raise concerns about potential economic and social consequences, including:
- A decline in local property and land values.
- Conflicts with local farmers, particularly where contamination could affect the safety or marketability of agricultural products.
- Potential remediation costs that may exceed the financial capacity of the municipality.

These concerns may discourage some local administrations from actively investigating or

openly reporting soil contamination problems, particularly in the absence of clear legal obligations or external support. Consequently, a reluctance to identify potential problems may develop, driven by concerns about the municipality's reputation, investment attractiveness, and possible financial responsibilities. This discrepancy highlights the need for improved environmental monitoring, more effective knowledge transfer, and practical training to strengthen the capacity of local administrations to identify, assess, and manage land and soil degradation.

Despite these limitations, the PoLaRecCE survey clearly identifies several common soil degradation threats, including flooding, soil erosion, industrial and urban dust deposition, soil sealing, and inappropriate waste management, which affect most of the surveyed regions to varying degrees. These processes reflect the combined impacts of climate variability, urban expansion, and historical industrial activities. At the same time, other localized but equally significant problems have been identified, such as cyanide contamination in Liguria and Silesia, soil degradation related to sewage and wastewater management in Slovenia, and severe agricultural soil degradation in Hungary. This diversity illustrates how soil health is influenced not only by natural factors, such as geology, climate, and topography, but also by region-specific economic development, historical industrial activities, and land-use practices.

The study highlights that soil degradation in the CE region is both widespread and diverse in its forms and causes. Addressing this challenge requires coordinated strategies to tackle common threats, combined with targeted interventions adapted to specific regional conditions. Strengthening the capacity of local administrations to identify, monitor, and manage soil degradation will be crucial for protecting soil resources, promoting sustainable land use, and preventing further biodiversity loss across Central Europe. The findings of the PoLaRecCE survey therefore confirm the need for accessible environmental databases, practical soil assessment tools, and clear guidelines that will enable local administrations to make informed decisions on the sustainable management and recovery of degraded land.

Where to find data on land and soil degradation?

European databases

Before consulting national databases, local administrations can obtain valuable information on soil health at the European and regional levels from freely accessible EU data sources.

European Soil Data Centre (ESDAC) / EU Soil Observatory (EUSO)

Both initiatives are managed by the European Commission's Joint Research Centre (JRC). One of the most important sources of information available through ESDAC is the LUCAS Soil database, which contains the results of physical and chemical analyses of soil samples collected

across the European Union. The database includes information on soil properties and concentrations of PTEs, such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), lead (Pb), and zinc (Zn), depending on the sampling campaign and dataset. These data are particularly useful for assessing regional soil conditions, identifying large-scale contamination patterns, and comparing soil properties across European regions.

European Environment Agency (EEA)

The European Environment Agency provides environmental indicators, reports, and mapping resources related to soil contamination and the management of contaminated sites across Europe. These include information on contamination by heavy metals and assessments of the management of contaminated sites, including the historical indicator CSI 015. Such resources can help local administrations understand the broader regional and national context of soil contamination and identify potential environmental concerns requiring further investigation.

Although these European databases are valuable for regional comparisons and identifying potential soil degradation threats, their spatial resolution is generally insufficient for assessing contamination at individual sites or making detailed land-use decisions at the municipal level. Such assessments require more detailed national or local data and, where necessary, additional field investigations.

National Databases and Institutions (Main Sources of Information for Local Administrations)

The following section presents the main national databases and institutions in each CE country where local administrations (municipal and district offices) can obtain information on soil contamination and degradation, access geochemical data, and, where applicable, report identified environmental problems.

Poland

- Chief Inspectorate for Environmental Protection (GIOŚ): Responsible for the Monitoring of Arable Soil Chemistry programme, conducted as part of the State Environmental Monitoring system. The monitoring results are publicly available and are updated periodically. They provide valuable information on long-term changes in the chemical properties and contamination of agricultural soils in Poland.
- Polish Geological Institute – National Research Institute (PIG-PIB): One of the main sources of geochemical maps and spatial information on soil contamination in Poland. Its resources include the Detailed Geochemical Map of Poland at a scale of 1:25,000 and geochemical atlases of urban and industrial areas, including the Upper Silesian Industrial Region. These maps provide local administrations with valuable information on the spatial distribution of potentially toxic elements (PTEs), particularly lead (Pb), cadmium (Cd), zinc (Zn), and other

contaminants. They can help identify areas where more detailed soil investigations may be necessary.

- General Directorate for Environmental Protection (GDOŚ): Maintains the national Register of Historical Land Contamination, which contains information on sites affected by historical contamination. Regional Directors for Environmental Protection (RDOŚ) are responsible for maintaining and updating the relevant regional records, while district authorities (starosts) have specific legal responsibilities for identifying potential historical contamination and preparing lists of such sites for submission to the competent regional directorate. This register is particularly important for local administrations involved in spatial planning, redevelopment of brownfield sites, and land management decisions.

Austria

- Environment Agency Austria (Umweltbundesamt): Manages BORIS (Bodeninformationssystem), the Austrian Soil Information System, which provides access to soil data collected through national and regional monitoring programmes. The database contains information on soil properties, soil quality, and contamination, including concentrations of PTEs. It is a valuable source of information for local administrations assessing soil conditions and potential degradation risks within their municipalities.
- Register of Suspected Contaminated Sites and Atlas of Contaminated Sites (Verdachtsflächenkataster / Altlastenatlas): These official information systems provide data on sites with suspected or confirmed historical contamination, including former landfills and industrial areas. They are particularly useful for local administrations involved in spatial planning, land redevelopment, and the assessment of potential environmental risks associated with proposed construction projects.
- Austrian Contaminated Sites Portal (Altlastenportal / Altlastenatlas): The official national information system providing data on contaminated sites, former waste disposal areas, and industrial sites where significant contamination or environmental risks have been identified or are suspected based on preliminary assessments. Following legislative changes introduced in January 2025, the former Register of Suspected Contaminated Sites (Verdachtsflächenkataster) was discontinued, and relevant information is now available through the Altlastenportal. The portal provides interactive maps and site-specific information that can support local administrations in spatial planning, brownfield redevelopment, and assessing potential environmental risks before approving new land-use or construction projects.

Czech Republic

- Czech Geological Survey (ČGS – Česká geologická služba): Provides geological and geochemical maps, including regional geochemical datasets and information on the

distribution of PTEs in soils and other environmental materials. These resources can help local administrations identify areas potentially affected by natural geochemical anomalies or contamination resulting from historical industrial and mining activities.

- Czech Environmental Information Agency (CENIA): Provides access to environmental information systems and databases, including the System for the Registration of Contaminated Sites (SEKM – Systém evidence kontaminovaných míst). SEKM contains information on contaminated and potentially contaminated sites, including areas affected by historical industrial activities, waste disposal, and other sources of pollution. It is a valuable tool for local administrations involved in spatial planning, brownfield redevelopment, and the identification of sites requiring further environmental investigation.
- Central Institute for Supervising and Testing in Agriculture (ÚKZÚZ – Ústřední kontrolní a zkušební ústav zemědělský): Conducts monitoring and assessment of agricultural soils, including their chemical properties and contamination by potentially toxic elements, particularly heavy metals. The collected data support the assessment of agricultural soil quality and the identification of potential risks associated with soil contamination and agricultural land use.

Slovakia

- State Geological Institute of Dionýz Štúr (ŠGÚDŠ – Štátny geologický ústav Dionýza Štúra): The national geological research institution based in Bratislava, responsible for geological and geochemical mapping, including the development of geochemical atlases of Slovakia. Its resources provide information on the spatial distribution of chemical elements and the identification of geochemical anomalies, including those associated with historical mining and industrial activities in regions such as Spiš and the Hron Valley. These data can help local administrations identify areas potentially affected by soil contamination and assess the need for more detailed environmental investigations.
- Ministry of the Environment of the Slovak Republic (MŽP SR – Ministerstvo životného prostredia Slovenskej republiky): Responsible for the national Environmental Burdens Information System (IS EZ – Informačný systém environmentálnych záťaží), which provides information on sites affected by confirmed or suspected environmental contamination, including contaminated soils and groundwater. This publicly accessible system is an important source of information for local administrations involved in spatial planning, brownfield redevelopment, and the assessment of environmental risks associated with historical industrial and waste disposal activities.

Hungary

- Supervisory Authority for Regulatory Affairs (SZTFH – Szabályozott Tevékenységek Felügyeleti Hatósága): Since January 2022, this authority has taken over the responsibilities of the

former Hungarian Mining and Geological Service (MBFSZ – Magyar Bányászati és Földtani Szolgálat). It provides access to geological and geochemical information, maps, and national geological datasets. These resources can help local administrations identify natural geochemical anomalies, assess geological conditions, and recognize areas potentially affected by historical mining and industrial activities.

- National Environmental Information System (OKIR – Országos Környezetvédelmi Információs Rendszer): The national system for collecting, managing, and providing environmental information in Hungary. It includes data on environmental conditions, pollution sources, and contamination of soil, geological materials, and groundwater. Of particular importance is the FAVI system (Felszín alatti víz környezetvédelmi nyilvántartási rendszere), which contains information on groundwater and geological contamination, including contaminated sites and remediation activities. These data can support local administrations in identifying potential environmental risks, assessing historical contamination, and making decisions related to spatial planning and land redevelopment.

Slovenia

- Slovenian Environment Agency (ARSO – Agencija Republike Slovenije za okolje): Provides environmental monitoring data and information on soil quality and contamination in Slovenia. Its resources include reports, monitoring results, and maps showing the distribution of PTEs, particularly heavy metals, in soils. These data are especially relevant to areas affected by historical industrial and mining activities, such as Celje and the Mežica Valley. They can help local administrations identify potential soil contamination problems and assess the need for further environmental investigations.
- Geological Survey of Slovenia (GeoZS – Geološki zavod Slovenije): Conducts geological and geochemical investigations and provides maps and spatial data on the geological and geochemical characteristics of Slovenia. Its resources include information on natural geochemical background levels and the distribution of chemical elements in soils and other geological materials, including studies of urban environments such as Ljubljana. These data can help local administrations distinguish between naturally elevated concentrations of potentially toxic elements and contamination associated with human activities.

Croatia

- Ministry of Environmental Protection and Green Transition (MZOZT – Ministarstvo zaštite okoliša i zelene tranzicije): The national authority responsible for environmental protection and environmental information systems in Croatia. Through its environmental information resources, including data previously managed by the Croatian Agency for the Environment and Nature (HAOP), it provides information relevant to soil quality, pollution sources, and environmental pressures. These resources can help local administrations identify potential

soil degradation problems and obtain information useful for spatial planning and environmental management.

- Croatian Geological Survey (HGI – Hrvatski geološki institut): Conducts geological and geochemical investigations and develops geological and geochemical maps of Croatia. Its resources provide information on the distribution of chemical elements in surface materials and the natural geochemical background. These data can help local administrations identify geochemical anomalies, distinguish natural element concentrations from potential anthropogenic contamination, and determine where more detailed soil investigations may be necessary.

Italy (Northern: Piedmont, Lombardy, Liguria, Emilia-Romagna)

- Italian Institute for Environmental Protection and Research (ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale): The national public research and technical institution responsible for environmental monitoring, assessment, and the collection and analysis of environmental data. ISPRA provides information on soil quality, land degradation, and contaminated sites, including data on Sites of National Interest (SIN – Siti di Interesse Nazionale), which are large or environmentally significant contaminated areas requiring remediation under national responsibility. These resources can help local administrations identify major contamination problems and obtain information relevant to spatial planning and land management.
- Regional Environmental Protection Agencies (ARPA/APPA), including ARPA Liguria, ARPA Lombardia, ARPA Piemonte, and ARPAE Emilia-Romagna: These regional agencies provide environmental monitoring data, technical assessments, and information on soil contamination at regional and local levels. Depending on the region, their resources may include data on contaminated sites, industrial pollution, and the chemical quality of urban, agricultural, and other soils.

Eastern German states (Saxony, Thuringia, Brandenburg, Saxony-Anhalt, Mecklenburg)

- State Environmental and Geological Agencies (Landesämter), including the Saxon State Office for Environment, Agriculture and Geology (LfULG – Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie): In Germany, responsibility for environmental protection and soil management is shared between the federal government and the federal states (Länder), with the latter playing a major role in implementing environmental legislation. State environmental and geological agencies provide soil monitoring data, geological and geochemical maps, and information on soil contamination and degradation. Their organisational structures and responsibilities vary between federal states. These institutions are important sources of information for local administrations assessing soil

conditions, identifying potentially contaminated areas, and planning appropriate land management measures.

- Registers of Contaminated Sites (Altlastenkataster): The German federal states maintain registers or information systems covering contaminated and potentially contaminated sites, including former industrial facilities, waste disposal areas, and sites affected by historical mining activities. These records are particularly relevant in industrial and former mining regions, such as Saxony and Saxony-Anhalt, where historical industrial activities have left a legacy of soil and groundwater contamination. Local administrations can use the available information to identify potential environmental risks and support spatial planning, brownfield redevelopment, and decisions concerning further site investigations or remediation.

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