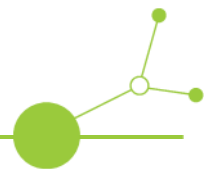


Action plan development for soils degraded by urban and industrial deposition of PTEs

Best available practices and on-site techniques for environmental site assessment and soil recovery



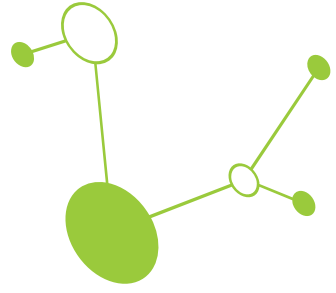
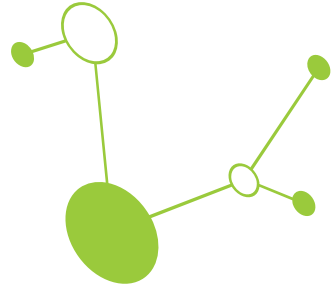




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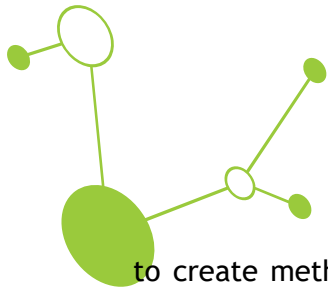
1. Introduction

Soils degraded by urban and industrial deposition of potentially toxic elements (PTEs) are not a local problem. Urban and industrial deposition has led to widespread soil contamination by potentially toxic elements across Central Europe. During the analysis of the problem identified on the basis of questionnaires sent to municipalities in selected regions of Central Europe (CE), 30 to 40% of the surveyed municipalities indicated this form of land degradation as a significant issue. This pattern reflects the historical concentration of industrial activity in specific regions, as well as the persistence of air pollution in urbanized and industrialized regions.

Long-term emissions from coal-fired power plants, metal smelters, traffic (brake/tire wear, exhaust), and legacy industries have deposited metals such as lead (Pb), cadmium (Cd), zinc (Zn), mercury (Hg), and arsenic (As) onto urban and peri-urban soils. These contaminants accumulate in topsoil for decades, and are often unevenly distributed (hotspots near roads, factories, and former industrial sites) or even migrate downward to the soil profile. This exerts serious threat to human health (especially children via dust ingestion) and ecological stress (toxicity to soil biota, reduced soil functions), along with food-chain transfer when urban gardens or nearby farmland are affected.

In many industrial or post-industrial regions of CE, where the agricultural or marginal soils are contaminated by various types of pollutants, the sustainable management of soil resources is an administrative and social challenge. In many cases these soils are still used for growing food and feed, leading to uncontrolled uptake of pollutants into the food chain. On the other hand, post-industrial marginal lands are often unused (uncultivated and unseeded) and lie fallow for many years before finally being designated for commercial and service zones, industrial halls, or warehouses. This process involves land sealing, which results in the complete loss of their productive functions.

The initial survey conducted in the frame of PoLaRecCE project revealed also the problem of limited knowledge of local administration and landowners about the actual state of chemical soil degradation in marginal and post-industrial areas. Typically, such studies, which involve a large number of chemical analyses, are very expensive and time-consuming, therefore there is a need



to create methods, tools and procedures for a quick, preliminary assessment of the quality of these soils and their suitability for agricultural use or the need for their remediation.

The aim of the PoLaRecCE project is to develop strategy and action plan for stepwise procedure of environmental site assessment and soil recovery of lands degraded by urban and industrial deposition. These innovative tools and approaches should support land management practices to better adapt degraded and contaminated soils to the environmental, social and economic needs of the local community. This activity is in line with the EU Green Deal policy and is a response to the challenges of environmental degradation and climate change.



2. Methodology

Building of the strategy and action plan for management of soils degraded by urban and industrial deposition of PTEs consists of five elements (Figure 1):

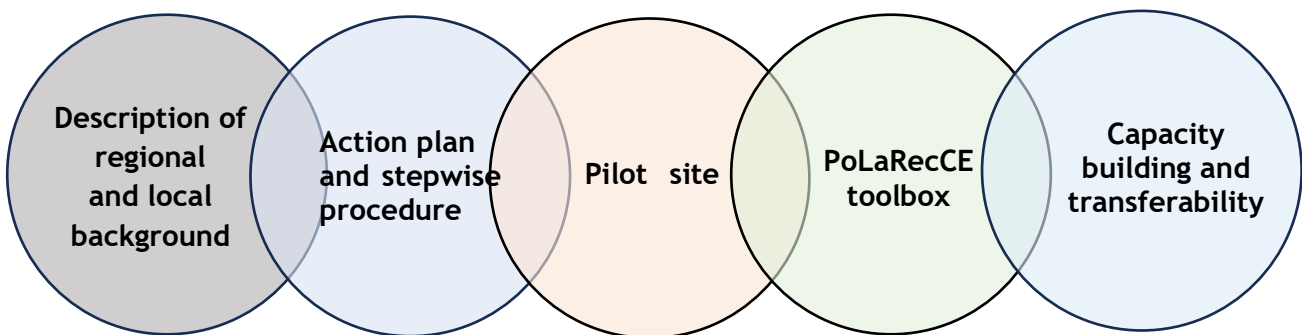


Figure 1. Five-element PoLaRecCE strategy diagram

The background section constitutes the analytical part of the study, identifying and monitoring emerging issues and signals of change in both the internal and external environment, while describing the current situation at the regional and local levels. Primary step is to properly identify driving forces and evaluate the state of the art with collection of **background data** concentrated on the situation in urban and industrial regions of southern Poland and particularly in Kraków metropolitan area and neighboring complex of settling units including also Skawina municipality.

The starting point of each **action plan** is the clear vision and strategy for the plan as the most interactive stage of the process is devoted to the development of goals, alternatives solutions in reaction to the identified challenges, problems and potentials. An expected outcomes of the plan and associated objectives and targets should be developed and assessed from the point of their coherence, achievability and responsibilities of actors. Different scenarios should be considered discussed and assessed. They should be confronted with existing local, regional and national policies. Finally, the **stepwise procedure** should be developed to ensure control, better planning



and efficiency by carrying out activities in a specific sequence, often based on management functions: planning, organizing, leading and controlling.

The procedure was tested at a **pilot site** located in the Skawina municipality. The optimal solution was selected from several possible alternatives, taking into account local environmental conditions, climate change impacts, social circumstances, and the investment financing model, as well as a cost-benefit analysis for end users.

Capacity building involves the development of skills and the enhancement of competencies among local and regional authorities, landowners and managers, as well as individual farmers and members of farmers' organizations. It improves institutional structures, management practices, and operational strategies at various levels through training, mentoring, exchange of experience, and improved access to technology and financing. A crucial element of the strategy is **transferability**, understood as the potential to apply the developed solutions in other areas of Central Europe degraded by the deposition of potentially toxic elements (PTEs) resulting from historical or ongoing urban and industrial soil contamination.



3. Background

3.1 Regional background

Southern Poland, including the Silesian Voivodeship and the western part of the Lesser Poland Voivodeship, is one of Europe's most industrialized and urbanized regions (Figure 2). Lead and silver mining in this area, as well as salt mining in Wieliczka and Bochnia (east of Kraków), began in the Middle Ages. Large-scale industrialization began at the end of the 18th century with coal mining, steel production, and lead, silver, and zinc smelting, and later expanded to heavy manufacturing and processing. Additional large industrial plants (e.g., the Katowice Steelworks, the Lenin Steelworks in Kraków, and the aluminum smelter in Skawina), as well as major coal-fired power plants, were built after World War II. Electrostatic precipitators were first installed on the chimneys of large industrial plants only in the late 1950s. As a result of industrial restructuring following the political transformation in Poland in 1989, a significant number of old and environmentally harmful industrial plants have been closed. Currently operating facilities are equipped with electrostatic precipitators and highly efficient dust removal systems. Dust emissions have drastically decreased compared to 1989 levels. However, pollutants deposited over more than 200 years of industrial activity will remain in the soil for hundreds of years. Heavy metals and other potentially toxic elements (PTEs) bind strongly to soil particles and persist for decades. Long-term deposition of industrial dust, combined with the region's increasing urbanization, has led to significant and persistent soil degradation and contamination. One of the key groups of pollutants in topsoil are PTEs, which pose a serious threat to local agriculture and food production. For this reason, a significant portion of former agricultural land has been excluded from agricultural use. This has caused a long-term decline in soil health, fertility, and the capacity to support plant growth and safe food production.

As a result, a significant portion of land has been removed from agricultural production and now lies fallow. On the other hand, some land remains in food production despite exceeding permissible standards for certain pollutants (e.g., PTEs). In many cases, there is a lack of detailed knowledge about the condition of soils on land withdrawn from production, as such areas are generally not subject to comprehensive environmental site assessments. Using of classical geochemical methods is expensive and time-consuming for both individual landowners and local



authorities. Moreover, a potential administrative decision to exclude still agriculturally active soils from food production would deprive local farmers of their livelihoods without providing alternative sources of income and would increase the area of unused lands. For this reason, it is necessary to develop a regional strategy defining procedures and methods for the rapid and cost-effective assessment of soil contamination levels and agricultural suitability in areas degraded by the deposition of industrial and urban dust and associated chemical pollutants. The strategy should also include methods for restoring soil productivity and enabling their use for non-food agricultural purposes.

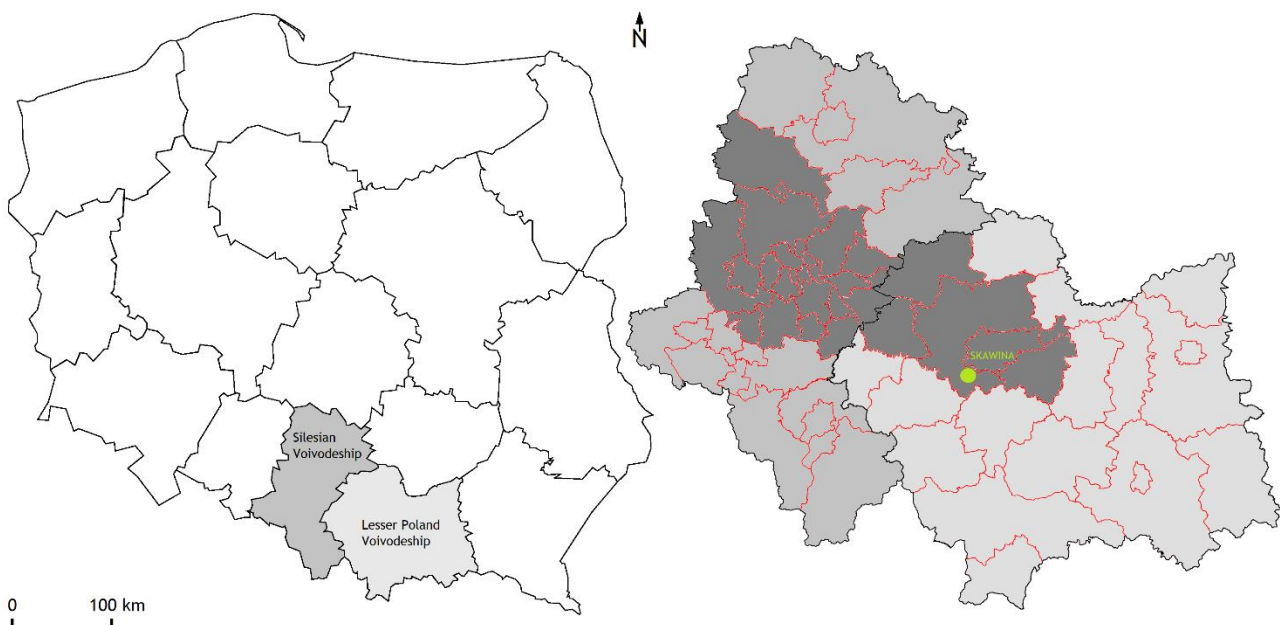
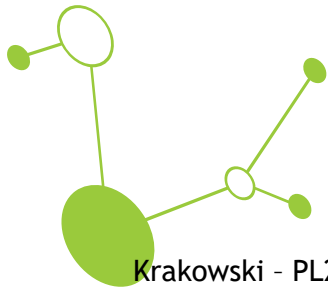


Figure 2. Location of the Skawina pilot site and regions of Poland with the highest historical deposition of industrial and urban dusts and the highest share of soils chemically degraded by potentially toxic elements in the topsoil

3.2 Local background

The investigated Skawina pilot site has been affected by long-term pollutant emissions from the aluminum smelter and power plant, as well as by dust emissions from their waste disposal sites. The Skawina pilot site is located in the Lesser Poland Voivodeship, in southern Poland (NUTS 3 -



Krakowski - PL214). The pilot site has a rectangular shape (ETRF 2000 - PL/CS92 GPS coordinates: A 49.980349 N, 19.798027 E; B 49.980339 N, 19.798994 E; C 49.979609 N, 19.797981 E; D 49.979586 N, 19.798965 E). It lies within the direct range of historical and current emissions from two large industrial plants: the Skawina Aluminum Works, opened in 1954, and the Skawina Power Station, which went online in 1961. The crucial section of the aluminum works (the Electrolysis Section) was closed in 1981 due to the widespread pollution it caused. The Skawina Power Station remains active. According to a World Health Organization report from 2016, Skawina was ranked twelfth among the most polluted cities in the European Union. However, due to great efforts by the local administration and actions taken by the municipality to eliminate local pollution sources, air quality has significantly improved in the second and third decades of the 21st century. Despite this, pollution accumulated in the topsoil remains a major problem for land quality and agricultural use. Currently, the nearest pollution source is a slag and ash storage dumping site located about 300 m west of the pilot site. The area of the pilot site selected for testing the PoLaRecCE strategy covers 4,500 m².

The Skawina region is located in a temperate, warm, transitional climate zone. In this zone, oceanic influences from the west and continental influences from the east converge, resulting in high weather variability. The average annual air temperature in 2020 was 10.0°C, compared to 8.7°C for the decade 2001-2010 and 8.1°C for the thirty-year period 1971-2000. The average temperature has been visibly increasing over the years due to global climate warming. The warmest month in 2020 was August, with an average temperature of 20.3°C, while for the decade it was July (19.8°C), and for the thirty-year period also July (17.8°C). The coldest months are January and December, with average temperatures of 1.0°C in 2020, -2.2°C for the decade, and -2.3°C for the thirty-year period. The total annual precipitation was 671.8 mm in 2020, 719 mm for the decade (2001-2010), and 562 mm for the thirty-year period (1971-2000). The highest annual precipitation total over the last 30 years was 1,029.9 mm, recorded in 2010 (when the commune experienced a flood), while the lowest was 448.4 mm in 1993. The greatest precipitation in 2020 occurred during the summer season (June-August), and the least during the winter season (December). On average, the rainiest month is August, while January and December are the driest. The lowest monthly precipitation total in 2020 was recorded in April (4.4 mm), and the highest in August (108.6 mm). A relatively high precipitation total was also recorded in October (95.9 mm).



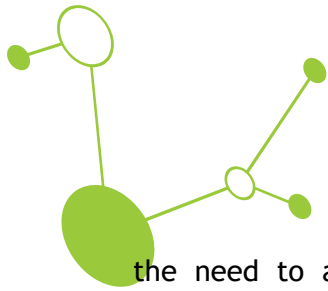
4. Action plan

4.1 Recognizing of the problem (PoLaRecCE - EU-policy)

In Central Europe (CE), the sustainable management of agricultural soils contaminated or degraded by chemical pollution resulting from industrial and urban deposition poses significant administrative and social challenges. Contaminated soils are typically removed from production and become wasteland, representing a substantial loss of the soil's biological potential. There is a lack of common and harmonized guidelines that could be applied across countries and administrative levels. The procedures developed within the project enable effective soil condition assessment based on innovative, predominantly field-based measurement techniques and methodologies. This makes it possible to evaluate the suitability of degraded soils for direct non-food agricultural production or to determine the need for reclamation measures aimed at restoring their biological activity and productivity.

The assumptions of the PoLaRecCE project are fully aligned with the European Union's policy on reducing environmental pollution and restoring the functional value of degraded areas. The main objective of the Soil Monitoring Law (Directive (EU) 2025/2360), as well as the PoLaRecCE strategy, is to reduce soil pollution to levels that are no longer considered harmful to human health and the environment. The practical implementation of the project strategy will contribute to the gradual improvement of soil conditions in the Silesian and Kraków regions and may be adopted in other post-industrial and highly urbanized regions of Central Europe and the entire EU territory. This project represents one of the first comprehensive attempts to improve the quality of soils degraded by industrial and urban deposition in order to achieve healthy soils by 2050, given that soils host more than 25% of global biodiversity and constitute the second-largest carbon pool on the planet. Healthy soils, which capture and store carbon, also contribute to achieving the Union's climate objectives. The project also represents an important step toward enhancing biodiversity, ecosystem functions and services, ecological integrity, and connectivity, in line with the Convention on Biological Diversity.

Finally, the PoLaRecCE project strategy aims to develop innovative tools and approaches that support land management practices to better adapt degraded soils to the environmental, social, and economic needs of local communities. The guidelines developed within the project emphasize



the need to assess soil condition before restoring its productive role in order to propose appropriate land management directions.

4.2 Effective environmental site assessment procedure (Ecological Services)

EFFECTIVE ENVIRONMENTAL SITE ASSESSMENT PROCEDURE is a fundamental element in the development of strategies for the recovery of degraded agricultural land for purposes other than food production.

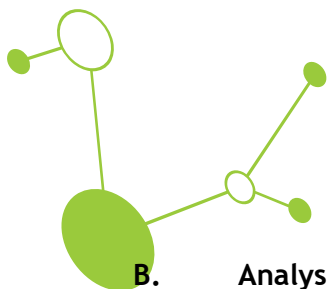
The starting point is:

A. Characterization of the site based on existing/current soil and climatic conditions

This characterization includes the following elements:

1. Geographical location of the site (geographic coordinates, province, municipality, land use). Graphical representation based on GIS tools.
2. Climatic conditions (based on multi-year data) taking into account parameters such as: length of the growing season, average annual air temperatures, average temperatures during the growing season, amount of precipitation during the growing season, length of the frost-free period).
3. Current soil conditions (soil type and subtype, fertility class) including the determination of the degree of soil degradation based on national and EU legal acts (e.g. **Directive (EU) 2025/2360**) Determining the sources and causes of soil degradation based on historical data.

Environmental assessment of the site and its immediate surroundings, including the state of habitats and valuable existing fauna and flora species. Determining whether there are any protected areas nearby according to Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora; Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds.



B. Analysis of potential directions of land development and use within the framework of current environmental conditions and local land development plans within individual municipalities

Local land development plans should consider assumptions at the regional level. A Regional Climate and Energy Action Plan has been established for the Małopolska Voivodeship (**Annex No. 1 to Resolution No. 228/20 of the Małopolska Voivodeship Board of 18 February 2020**).

One of the goals of the European Union's climate and energy policy until 2030 is to increase the share of energy from renewable sources to at least 32% of gross final energy consumption. Energy plantations are part of this goal.

C. Ecosystem services

Soils are considered as important and strategic natural capital. Soil ecosystem services can bring provisions in nutrition, materials and energy, can bring also mediation of wastes, toxic elements. In addition, non-degraded areas can provide cultural services (physical, spiritual and symbolic interactions with soil biota or landscape). Quantity and quality of soil ecosystem services depend on proper management. On degraded areas soil cannot be capable to fulfill all its services, especially food production.

The determination of the potential of ecosystem services results from the implementation of the following stages:

1. Initial State - Analysis of applicable legislation and strategic plans at the local and regional levels. Identification of existing obstacles and assessment of factors encouraging the development of degraded soils.
2. Advanced stage - creation of recommendations and tools at the municipal level to support the management of degraded soils.
3. Assessment of soil ecosystem services in each project (Table 1).

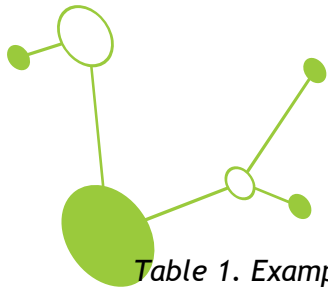


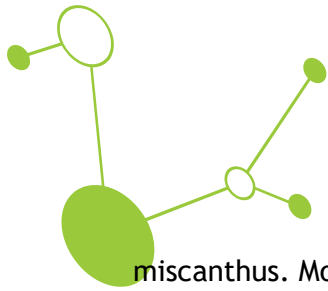
Table 1. Example of table for assessment of soil ecosystem services

Service	Service Importance Level				
	Pivotal	Important	Necessary	Not necessary	Irrelevant
Soil forming					
Water retention					
Mitigating the effects of climate change					
Immobilization/filtering of pollutants					
Nutrient cycling					
Biomass production for energy purposes					
Food production					
CO ₂ sequestration					
Aesthetic, cultural and landscape functions					

4.3 Considered solutions for the recovery of soil degraded by urban and industrial deposition of PTEs

The selected land management direction for the Skawina pilot site is the establishment of a plantation of giant miscanthus (*Miscanthus × giganteus*), intended for non-food agricultural use and renewable energy biomass production. Based on environmental assessment, the soil conditions were deemed suitable for non-food perennial crops. Miscanthus was chosen as a highly resilient species capable of thriving on degraded soils while providing long-term ecological and economic benefits. Miscanthus offers a combination of agronomic, environmental, and economic advantages, making it particularly suitable for the rehabilitation of degraded areas such as the Skawina pilot site.

Other energy crops, such as Virginia mallow (*Sida hermaphrodita*) or willow (*Salix* spp.), were considered for the Skawina pilot site. However, these species as well as energy poplar species require higher soil moisture, periodic maintenance, and higher planting costs compared to



miscanthus. Moreover, they are more sensitive to drought and poor soil aeration and have a short rotation cycle, requiring replanting after 6-8 years. Poplar is a viable option for intensive biomass production, but less durable and more management-intensive than perennial grasses. It could serve as a complementary species in mixed restoration systems. Taking into account the local circumstances, miscanthus was identified as the most suitable option, as it demonstrates lower cultivation requirements, greater carbon storage potential, and better adaptation to semi-contaminated sites. These characteristics make it an ideal candidate for demonstration within the PoLaRecCE project. A preliminary market assessment indicates a growing demand for sustainable biomass and renewable energy sources in Poland. Miscanthus can serve as an alternative to maize and traditional biomass for local heating plants, biogas producers, and eco-material industries.

Alternatives to energy crops in chemically polluted areas considered also for this pilot site were:

Plantation of Blue Spruce (*Picea pungens*), which is a conifer species with strong ornamental value and high tolerance to urban and industrial pollution. Blue Spruce can grow on moderately degraded soils and is often used for landscape restoration, noise reduction, and microclimate improvement around industrial zones.

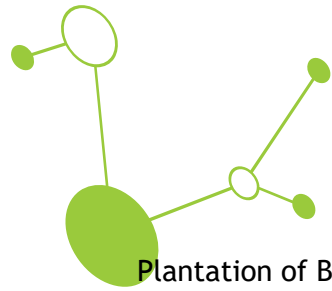
Advantages:

- High aesthetic and decorative value (potential use as Christmas trees or landscape greenery).
- High tolerance to low temperatures, drought, and moderate pollution.
- Improvement of air quality and soil protection against erosion.
- Long lifespan and low maintenance requirements once established.

Disadvantages:

- Slow growth rate - economic benefits appear only after many years.
- No direct biomass or energy use potential.
- Requires regular pruning and care in the first years after planting.
- Limited soil remediation effect compared to perennial grasses like Miscanthus.

Therefore, while Blue Spruce offers environmental and social benefits, it is less suitable for short and medium-term biomass production or economic recovery of degraded lands.



Plantation of Bamboo (*Phyllostachys spp.*) was the other considered alternative solution. Bamboo is a fast-growing grass species increasingly considered for biomass and green architecture applications. Although it offers remarkable productivity in warmer climates, its potential in Central Europe is limited by winter frost tolerance.

Advantages:

- Extremely fast growth and high biomass yield in optimal conditions.
- Potential use for bio-based construction materials.
- Aesthetic and ecological landscape function.

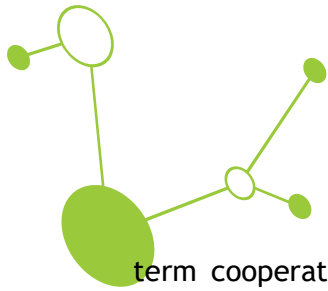
Disadvantages:

- Low frost resistance - risk of damage in Polish climatic conditions.
- Requires careful management to prevent uncontrolled spreading (invasive potential).
- High initial planting costs and uncertain market value in the region.

In summary, bamboo remains an experimental or decorative option for small-scale trials, but not a practical large-scale solution for degraded lands in the Skawina area, but it is alternative for the areas located in more suitable climatic condition of CE territory.

4.4 Initiation and activation of local administration land owners

The activation of citizens and local farmer groups, as well as active collaboration with local administrations and landowners, constituted a core horizontal activity of the PoLaRecCE project and was pursued through a combination of early engagement, targeted dissemination, and field-based cooperation. The process was initiated during the Kick-off Meeting in Skawina, Poland (19-21 June 2024), which marked the formal launch of the project and the establishment of cooperation with local authorities. The meeting, opened by representatives of the Municipality of Skawina and scientists from the Institute of Environmental Engineering of the Polish Academy of Sciences, highlighted the role of municipalities in addressing soil degradation. The project objectives, governance structures, communication approaches, and the Interreg Central Europe framework were discussed with all relevant stakeholder groups. This established the basis for long-



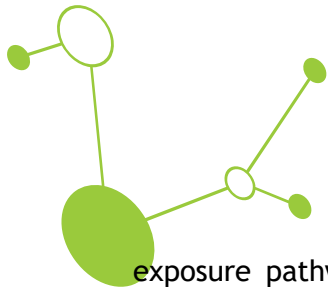
term cooperation focused on remediation and non-food land use. International meetings and events should be used to disseminate the project strategy among professional stakeholders, companies, and institutional representatives from the agricultural, environmental, and bioeconomy sectors in order to increase its visibility and support networking activities relevant to soil restoration and land management.

Technical exchange visits to pilot sites where solutions have already been implemented, combined with meetings involving local authorities and stakeholder organizations, are an effective tool for knowledge transfer. Also the field visits to see already existing solutions in different regions of CE are the part of the PoLaRecCE activities. On-site discussions can facilitate the exchange of practical knowledge on soil diagnostics, pollution sources, and remediation options, while supporting the identification of site-specific challenges and opportunities for non-food land use. Educational and awareness-raising activities may serve as an important complementary pathway for long-term stakeholder engagement. Dissemination activities targeting high school students and the broader educational community are also part of this strategy.

Overall, the activation of local administrations and landowners should be achieved through consistent engagement, alignment with policy frameworks, and the combination of scientific expertise with practical, field-based interaction. These actions will strengthen cooperation between research institutions and local stakeholders and support informed decision-making for the revitalization of degraded and contaminated land.

4.5 Influence of national legislative for implementation of „Action plan”

The strategy developed for soils degraded by the urban and industrial deposition of PTEs and implemented at the Skawina pilot site is aligned with Polish national policies on environmental protection, land management, and regional transformation, as well as with the local Municipal Revitalization Program. The risk-based remediation approach adopted by the municipality reflects the current national regulatory philosophy, which prioritizes achieving an acceptable environmental condition rather than restoring pristine pre-industrial soil conditions. Polish legislation allows for differentiated land-use scenarios depending on contamination risk and



exposure pathways. In the case of Skawina, environmental assessments confirmed that while localized exceedances of certain potentially toxic elements (PTEs) occur, the site does not require full technical remediation for non-food agricultural purposes. This approach ensures consistency with national environmental protection objectives while enabling economically viable land reuse.

The Action Plan also directly contributes to the objectives of the Regional Development Strategy, which emphasizes environmental regeneration, climate adaptation, and the sustainable economic transformation of post-industrial zones. The Municipality of Skawina is a part of the Kraków Functional Urban Area and plays a strategic role in the transformation of industrial zones within the metropolitan system. The selected pilot site lies within the historical emission range of two major industrial plants: the Skawina Aluminum Works (established 1954; electrolysis section closed in 1981) and the Skawina Power Plant (operational since 1961). Although air quality has significantly improved in the 21st century due to local mitigation efforts, accumulated contamination in topsoil remains a constraint for conventional agricultural use.



5. Pilot site and economic development

The comparative analysis of land management options for the Skawina pilot site – including giant miscanthus (*Miscanthus × giganteus*), Blue Spruce (*Picea pungens*), Virginia mallow (*Sida hermaphrodita*), willow (*Salix* spp.), energy poplar (*Populus* spp.), and bamboo (*Phyllostachys* spp.) – indicates that *Miscanthus* represents the most effective and sustainable solution for the rehabilitation and utilization of degraded land. From an environmental perspective, *Miscanthus* provides substantial benefits through soil stabilization, erosion control, and carbon sequestration. Its perennial growth and dense root system enhance soil structure and long-term fertility while limiting contaminant mobility.

5.1 Financial model for investment

Following the pre-feasibility assessment, a wood biomass plantation has emerged as the preferred intervention. This approach aligns with Poland's renewable energy strategy and the municipality's dual objectives of soil remediation and productive land use. The investment aims to establish a dedicated biomass plantation. It will supply the growing demand for renewable energy, while also providing employment opportunities and environmental co-benefits.

Poland is a significant player in Europe's biomass market. It accounts for 25% of renewable energy production from biomass and ranks as the continent's third-largest wood pellet producer. The logistics-intensive nature of biomass transport favours local production. Exports to Denmark and Germany demonstrate commercial viability. The plantation also enables Skawina to diversify its energy mix beyond fossil fuels.

Within the scope of the project it has been decided to try a pilot project of the biomass plantation, in order to verify the concept and enable the municipality to decide on expansion of the production based on the real life examples.

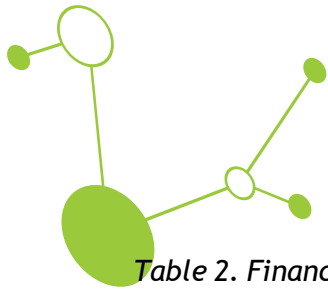


Table 2. Financial assumptions for the implementation the pilot action on the pilot site in Skawina

Assumption	Value
Inflation Rate	3% per annum
Discount Rate	4% per annum
Exchange Rate	1 EUR = 4.25 PLN
Corporate Income Tax Rate	9%

Table 3. Presentation of project costs, revenues, and assumptions for the Skawina pilot site

Cost category	Investment costs		Operational costs	
	PLN	EUR	PLN	EUR
Materials	10.000	2.354	200	47
Equipment	2.200	518	600	141
Personnel	7.200	1.695	1.000	235
Logistics	2.200	518	800	188
Taxes and Fees (municipal and land)	400	94	400	94
TOTAL	22.000	5.179	3.000	706

Financial assessment of the pilot

The pilot is not expected to cover its investment. Operational losses are projected at -600 EUR in year 2 and -431 EUR from year 3 onward. This outcome is expected, as the pilot's purpose is to serve as a proof of concept on a small plot of land. Operational costs at this scale are not fully utilizable. Results cannot be directly scaled to larger sites. The pilot provides valuable data for the municipality to assess feasibility for commercial-scale implementation without imposing a significant budget burden.

The operational cost structure demonstrates the efficiency characteristics of biomass production, with annual costs representing approximately 10% of initial investment. This low operational intensity, combined with extended productive life of more than 25 years (25 assessed in the financial model), contributes favourably to long-term financial viability.

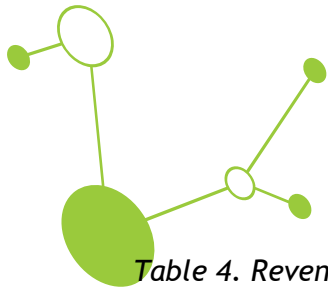


Table 4. Revenue projection in perspective of 25 years

Parameter	Value (PLN)	Value (EUR)
Biomass Yield (Year 2)	100 tonnes	100 tonnes
Biomass Yield (Year 3+)	250 tonnes	250 tonnes
Base Price (Year 2)	350 per tonne	82,39 per tonne
Annual Price Escalation	3%	3%
Revenue Year 2	35.000	8.239
Revenue Year 3	87.500	20.598
Revenue Year 25	167.659	39.467

Revenue generation commences in Year 2 with initial harvest, reflecting the typical maturation period required for biomass crops. The revenue model is predicated on two principal parameters: yield per hectare and market price, both subject to conservative assumptions to ensure financial projections maintain credibility. The table above summarises the key revenue parameters and projected outcomes.

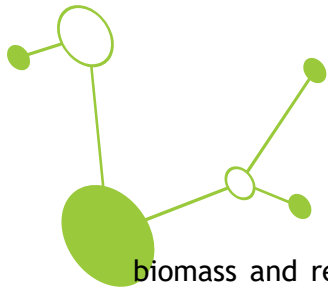
Biomass Yield

The financial model projects annual yield of 250 tonnes of dry mass from Year 3 onwards, following a reduced initial harvest of 100 tonnes in Year 2. This stepped approach recognises that newly established plantations require time to reach full productive capacity. The 250-tonne annual yield represents a conservative estimate based on Polish forestry data and comparable biomass plantation performance in similar climatic conditions.

The yield assumption accounts for the specific characteristics of fast-growing biomass species *Miscanthus × giganteus* suitable for energy production. The model assumes sustainable harvesting practices that maintain long-term (25 years +) plantation productivity whilst enabling annual biomass extraction.

Price Projections

The base price is set at PLN 350 per tonne (EUR 82.39 per tonne) of dry mass in Year 2, reflecting current Polish biomass market prices. This pricing reflects the wholesale market rate for energy



biomass and represents a conservative valuation compared to peak market prices observed in recent years.

The model incorporates 3% annual price escalation, aligned with the inflation assumption and reflective of the sustained upward pressure on biomass prices driven by increasing renewable energy targets, fossil fuel substitution, and supply chain constraints. This escalation is supported by historical market trends and forward projections for Poland's energy transition trajectory (Tables 2-4, Figure 3).

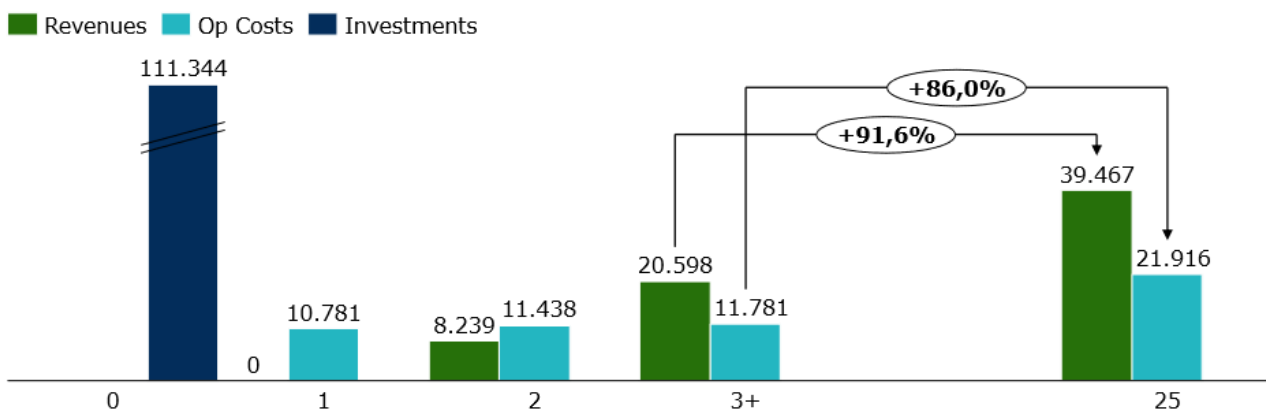


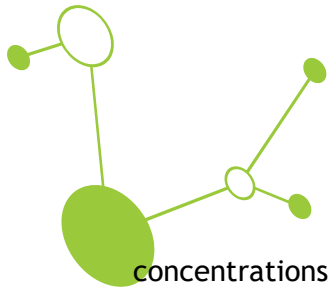
Figure 3. The chart projects the relevant project assumptions in the first 3 years, and showcasing the projected growth in prices and costs due to inflation between the year 3 and year 25

5.2 Cost-benefit analysis

While the pilot-scale plot is not intended to generate direct profit, the investment delivers substantial long-term environmental, social, and strategic benefits. These benefits support larger-scale applications.

Environmental Remediation and Pollution Reduction

Historical industrial activity and coal burning have degraded soils in the area. Phytoremediation using fast-growing biomass species is an effective method to remove contaminants, including heavy metals and organic pollutants. Over the 25-year project lifetime, contaminant



concentrations are expected to decrease. This will improve soil health and reduce risks to surrounding areas.

The plantation also mitigates soil erosion by stabilizing soil structure and reducing surface water runoff. Additionally, it functions as a carbon sink. It sequesters 5-10 tonnes of CO₂ per hectare per year, contributing to climate mitigation objectives.

Urban Regeneration and Landscape Enhancement

Transforming derelict industrial land into a productive green space enhances local aesthetics, supports biodiversity, and may increase adjacent property values. The project converts previously unused land into a productive asset. This demonstrates municipal commitment to sustainable development.

Recreation and Community Amenity

The plantation can provide informal green space, walking paths, and opportunities for outdoor education. Schools may use the site for experiential learning in forestry, renewable energy, and environmental management. Over time, the plantation provides shade, improves air quality, and supports passive recreation opportunities.

Employment Generation and Skills Development

The project creates direct employment during establishment and ongoing operations. It also supports skills development in forestry management, renewable energy, and sustainable land use. This may benefit youth employment programs and social enterprises.

Energy Diversification and Security

By producing local biomass, the municipality reduces reliance on fossil fuels. Local production shortens supply chains, improves energy security, and reduces transport-related emissions.

Strategic Positioning and Institutional Capacity

Managing the plantation enhances municipal capacity for complex, long-term initiatives. Successful implementation strengthens Skawina's credibility for future EU and national funding applications.



Summary of costs and benefits

The biomass plantation creates multi-dimensional value. It combines environmental protection, economic development, social inclusion, energy security, and institutional capacity building. The modest financial returns (money multiple of 1.03) are outweighed by extensive non-financial benefits. The project represents a sound use of public resources. It delivers returns beyond purely financial metrics.

5.3 Site specific actions for Skawina

The pilot action steps are:

1) Initial recognition of the environmental problem at the Skawina pilot site

Status: accomplished

- During the initial meeting on 20th of June 2024, representatives of the local authorities introduced the main environmental problems and health risks associated with long-term pollutant emissions from the aluminum smelter and power plant, as well as dust emissions from waste disposal sites, to all members of the PoLaRecCE project. On the same day, a field excursion to the Skawina pilot site was organized.

2) Implementation of the environmental site assessment procedure

Status: accomplished

Determination of the degree of soil degradation based on various field measurement techniques. At the same time, an assessment of soil ecosystem services was performed (Table 4). According to the collected data, the soil was characterized by moderate contamination and low organic matter content.

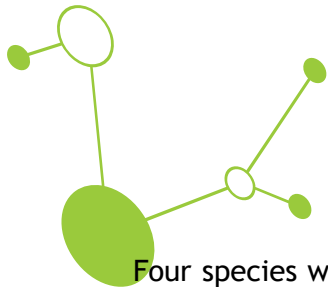
3) Construction of the financial model for the investment (milestone 1 - M1)

Status: accomplished

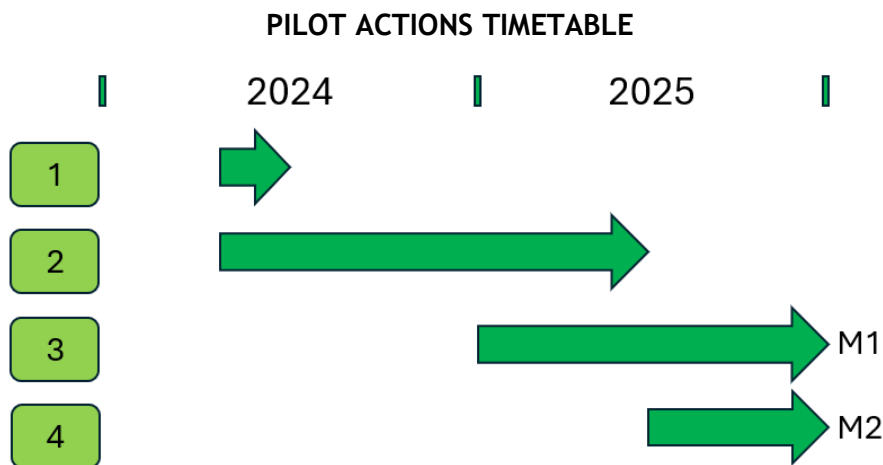
A detailed description of this step is provided in Chapter 5.1.

4) Selection of the best recovery solution for the degraded soil of the Skawina pilot site and establishment of the plantation (milestone 2 - M2)

Status: accomplished



Four species were considered for the pilot site: giant miscanthus (*Miscanthus × giganteus*), blue spruce (*Picea pungens*), energy poplar (*Populus spp.*), and bamboo (*Phyllostachys spp.*). Miscanthus was identified as the most effective and sustainable option.



5.4 Risk assessment for Skawina pilot site

The overall risk associated with the establishment and long-term operation of the *Miscanthus × giganteus* plantation in Skawina is assessed as moderate, primarily due to the relatively high initial investment costs and the uncertainty of future biomass market prices. The financial return on investment depends on long-term market stability and policy support for renewable biomass. The estimated payback period for Skawina investment is 14 years (undiscounted) or 19 years (discounted). Additionally, biomass price is susceptible for fluctuations and changes driven by climate or energy policy.

5.5 Ecosystem services for Skawina pilot site

Soil ecosystem services can bring provisions in nutrition, materials and energy, can bring also mediation of wastes, toxic elements. Site assessment is a first step prior determination of the potential of ecosystem services. The value of individual soil services should be determined for each project.

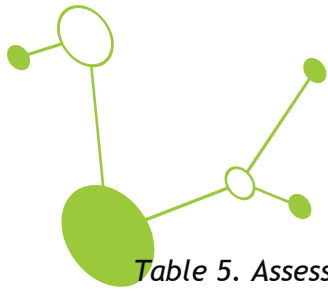


Table 5. Assessment of soil ecosystem services for Skawina pilot site

Service	Service Importance Level				
	Pivotal	Important	Necessary	Not necessary	Irrelevant
Soil forming				X	
Water retention		X			
Mitigating the effects of climate change		X			
Immobilization/filtering of pollutants	X				
Nutrient cycling				X	
Biomass production for energy purposes	X				
Food production					X
CO ₂ sequestration			X		
Aesthetic, cultural and landscape functions			X		



6. Durability, upscaling and dissemination plan

6.1. Durability model in practice

6.1.1. Durability models in practice

The Skawina municipality is adopting a multi-variant sustainability model that combines benefits for residents with energy security and education:

Concept 1: Promoting Cultivation among Residents (Priority) The Skawina municipality will provide *Miscanthus giganteus* seedlings (rhizomes) to residents free of charge, creating a distributed phytoremediation network. By planting the crop on their own land, residents will benefit from a natural air filter, a noise barrier (particularly effective along roads), and a potential source of biomass, which they may use according to their needs.

Concept 2: Municipal Energy Resource. The Skawina municipality will regularly harvest biomass from the site (once a year or every two years). The harvested material will be used for energy purposes by municipal units, supporting energy independence and the use of renewable energy sources at the local level. The Skawina Commune, as part of an energy cooperative, may apply for funding to build a dry biogas plant. It is already a member of a local energy cooperative planning to launch a dry fermentation biogas facility, for which high dry matter biomass will be a key resource. Biomass obtained from the site will be processed into fiber lengths optimal for the fermentation process, depending on the input requirements of the biogas plant. *Miscanthus* from the experimental site (as well as from residents' crops) is considered a valuable substrate for this installation. This approach will enable the local conversion of biomass into clean energy (biogas, electricity, and heat), thereby supporting a circular economy within the commune.

Concept 3: Hybrid Model and “Living Laboratory” This concept assumes resource sharing: half of the *Miscanthus* yield is distributed to residents (as seedlings or biomass), while the other half remains on the site. This ensures that the Skawina site continues to function as a permanent experimental and demonstration area for future generations, supporting education on soil remediation methods. The remaining biomass may also be used for energy purposes.



6.1.2. Financing

- Maintenance of the site and preparation of materials for residents will be financed from the Municipality's own budget (allocated to greenery and environmental protection). This represents a low-cost solution, ensuring stability after the subsidy period ends.
- External funding: The Municipality will monitor funding opportunities for additional equipment (e.g., chippers, briquette presses, or biogas plants within the energy cooperative) in order to provide residents with processed biomass in the future (e.g., in the form of pellets or energy/heat).

6.1.3. Promotion and Replication

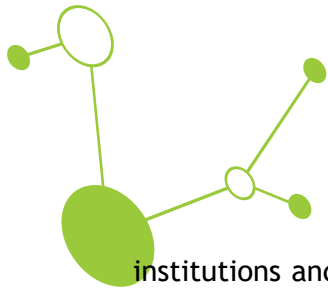
The initiative, launched under the banner of building a green energy network, demonstrates that the municipality is not only effectively addressing waste management challenges but also generating biomass resources through residents' active participation. This model follows a principle of adaptive (evolutionary) management: its scale and development will depend on monitoring results, the level of public interest, and the scope of the pilot project. Depending on local needs and the success of implementation, the model can be replicated and adapted by other municipalities in various forms.

6.1.4. Sustainability and Durability Mechanisms

The key long-term sustainability mechanism is the integration of the site into the ecosystem of the local energy cooperative. In this model, the cooperative would act as a biomass collection coordinator, ensuring a stable demand for raw material (*Miscanthus*) and its conversion into locally produced green energy (e.g., as a substrate for the planned dry biogas plant). However, it should be noted that the implementation of this step is conditional and depends on the cooperative's successful development, its full operational capacity, and the acquisition of the necessary external funding for the construction of the biogas infrastructure.

6.2. Comprehensive upscaling plan

Across all activities, the engagement and activation of local administrations and landowners were achieved through early involvement, targeted dissemination, field-based engagement, and alignment with EU policy frameworks. These actions strengthened cooperation between scientific



institutions and local stakeholders, supporting informed and sustainable decision-making for the revitalization of degraded and contaminated areas in other regions of southern Poland and Central Europe, where the problem of land degradation caused by urban and industrial deposition of PTEs persists (Figure 4).

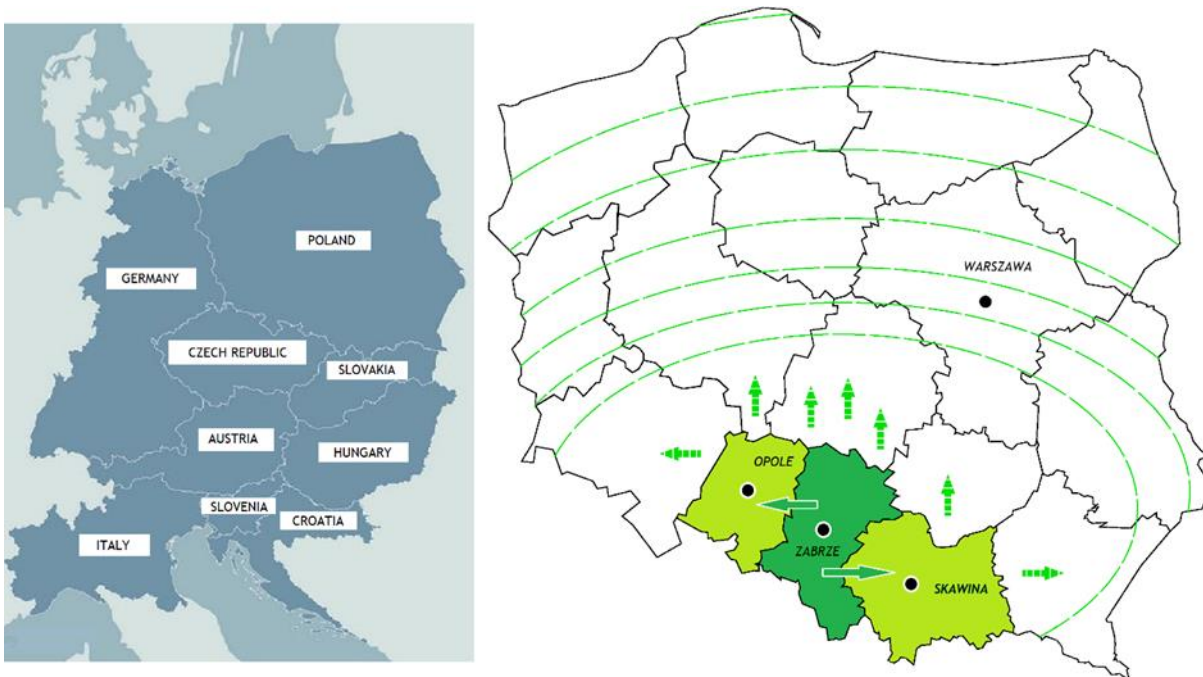
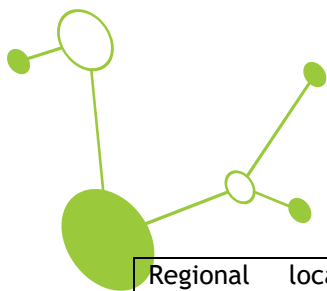


Figure 4. Integrated upscaling concept.

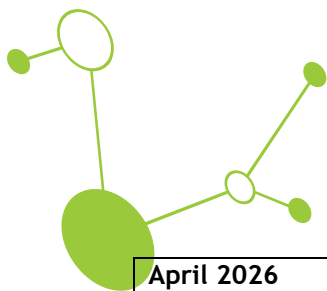
Upscaling plan

Table 6. Upscaling plan for the concept developed for soils degraded by urban and industrial deposition of PTEs.

Target group or area and timetable	Description
Local administration and stakeholders in Skawina (Poland) June-July 2024	A meeting with the local administration and a field excursion to degraded areas in Skawina enabled direct engagement with local conditions and facilitated open exchange on remediation and non-food agricultural management strategies, laying the groundwork for long-term cooperation with local stakeholders.
University of Bologna (Italy) September 2024	The integration of PoLaRecCE concepts into a master's thesis at the University of Bologna demonstrated effective knowledge transfer to higher education. Student engagement in project-related research supported the project's objectives and contributed to capacity building among future soil management professionals.



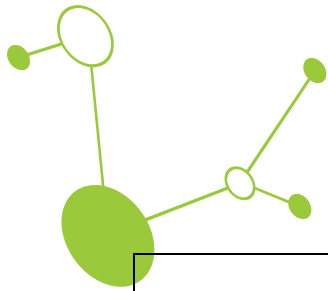
<p>Regional local and regional administration of Liguria Province (Italy)</p> <p>October 2024</p>	<p>The involvement of local and regional administration and the development of networks relevant to land management and soil restoration initiatives on polluted soils were achieved during meetings in Genoa and Cairo Montenotte.</p>
<p>Municipality Castenaso Emilia-Romagna (Italy)</p> <p>June - July 2025</p>	<p>A targeted meeting in the Municipality of Castenaso took place at the PoLaRecCE demonstration site and municipal office. Discussions focused on opportunities for rehabilitating polluted areas and innovative techniques to be demonstrated, including indicators for assessing soil status and recovery potential. This activity strengthened cooperation with local authorities and supported the preparation of demonstration actions.</p>
<p>University of Opole (Poland)</p> <p>October 2026 - June 2027</p>	<p>Incorporation of the developed PoLaRecCE solutions in the educational program of lectures and engaging students in project-related research initiatives, leading to capacity building relevant to future soil management professionals.</p>
<p>Local administration of municipalities Silesian Voivodeship (Poland)</p> <p>November - December 2025</p>	<p>The seminar and workshop in Zabrze for 15 Silesian municipalities aimed to present the PoLaRecCE solution developed for the Skawina pilot site. This meeting was dedicated to all regions where the problem of land degradation caused by urban and industrial deposition of PTEs persists.</p>
<p>Regional administration Podkarpackie Voivodeship (Poland)</p> <p>November - December 2025</p>	<p>The seminar and workshop held in Zabrze for representatives of the regional administration of the Podkarpackie Voivodeship (south-eastern Poland) aimed to present the PoLaRecCE solution developed for the Skawina pilot site, which is applicable to regions affected by land degradation resulting from urban and industrial deposition of PTEs.</p>
<p>City of Turin (Italy)</p> <p>Zadra Nova Municipality (Croatia)</p> <p>November 2025 - December 2027.</p>	<p>The submission of the WaSFA4CE project (“Water, Soil, Food and Air: reducing divisions and strengthening resilience in Central European urban and rural areas”) includes the capitalisation of previously developed PoLaRecCE solutions, as well as the application of the strategy developed for the Skawina pilot site in the City of Turin and the municipality of Zadar Nova.</p>
<p>Regional administration Opole Voivodeship (Poland)</p> <p>March - May 2026</p>	<p>The seminar and workshop in Opole are intended for the regional administration of the Opole Voivodeship and smaller local units, to present the PoLaRecCE solution developed for the Skawina pilot site, dedicated to regions where the problem of land degradation caused by urban and industrial deposition of PTEs persists.</p>
<p>Municipality of Ormož (Slovenia)</p>	<p>A meeting and workshop for local stakeholders, local administration, and communities (including schools) to present the solutions developed during the PoLaRecCE project.</p>



April 2026	
Institute for Ecology of Industrial Areas (Katowice) and Research and Innovation Centre Pro-Akademia in Konstancin Łódzki (Poland)	Sharing knowledge and experience with the partners of the MICROMAR+ project related to miscanthus cultivation and delivering robust agronomic practices for crop establishment on challenging MaCL soils, along with innovative biorefinery options for the circular bioeconomy.
April - June 2026	
Agricultural technical school in Silesian region (Poland)	Lectures at an agricultural technical school in Nakło Śląskie (Silesian Voivodeship, Poland) to present solutions developed for degraded soils.
September - November 2026	
Polish Soil Science Society	Promotion of the PoLaRecCE solution within the Polish soil science community to influence legislative developments applied at the national level during the implementation of Directive (EU) 2025/2360, the “Soil Monitoring Law.”
September 2026 - December 2028.	

6.3. Dissemination plan

Date of the event	Description	Responsible project partner (PP)
20 th of September 2024	The presentation of PoLaRecCE at the OPENDISTAL event supported early dissemination among researchers, companies, and institutional stakeholders from the agricultural, environmental, and bioeconomy sectors.	PP2
November 2024 - June 2025	Dissemination activities targeted on high school students and the wider educational community in Bologna and the Emilia-Romagna region. Through presentations, workshops, and hands-on activities, participants were introduced to soil functions, soil degradation, and remediation strategies for polluted land.	PP2
March 2025	The integration of PoLaRecCE concepts into a master’s thesis at the University of Bologna demonstrated effective knowledge transfer to higher education. Engaging students in project-related research supported dissemination	PP2



	objectives and contributed to capacity building for future soil management professionals.	
September 2025	The solutions developed for the PoLaRecCE pilot sites were presented at the EUROSIL 2025 Congress in Seville, Spain, as a poster on soil degradation, contamination, remediation strategies, and the adaptation of degraded land for non-food agricultural purposes.	LP and PP2
October 2025	The solutions developed for the PoLaRecCE pilot sites were also presented to the Commission on Soils of Urban, Industrial, Traffic, Mining and Military Areas during the 13th SUITMA Conference in Pisa, Italy.	LP and PP2
June 2026	The developed methodology for site assessment of areas polluted by urban and industrial deposition will be presented at the scientific conference <i>The Biennial Castle Meeting - New Trends in Rock, Paleo- and Environmental Magnetism</i> , held in Collonges-la-Rouge, Corrèze, France.	LP
June - July 2026	The developed methodology for site assessment of areas polluted by urban and industrial deposition of PTEs will be published in a high-ranking environmental science journal.	All project partners
September - October 2026	Case studies on the application of soil magnetometry in areas degraded by urban and industrial deposition of PTEs will be published.	LP
November 2026	The final toolbox/handbook, providing a set of procedures for quick, inexpensive, and effective environmental site assessment, as well as criteria for selecting the best available solutions for development and management strategies (with a special focus on non-food farming, including analysis of ecological and environmental benefits), will be published	All project partners
December 2026 - 2027	The handbook will be disseminated among local and regional administrations in Poland and other Central European countries.	All project partners
December 2026 - 2027	The final solutions and results of the project will be disseminated via social media in all participating countries.	All project partners



7. Policy tools/instruments

Policy Tools

In order to promote efficient management of the degraded lands PoLaRecCE project developed tools supporting strategic planning initiatives and improving multilevel governance (Figure 5).

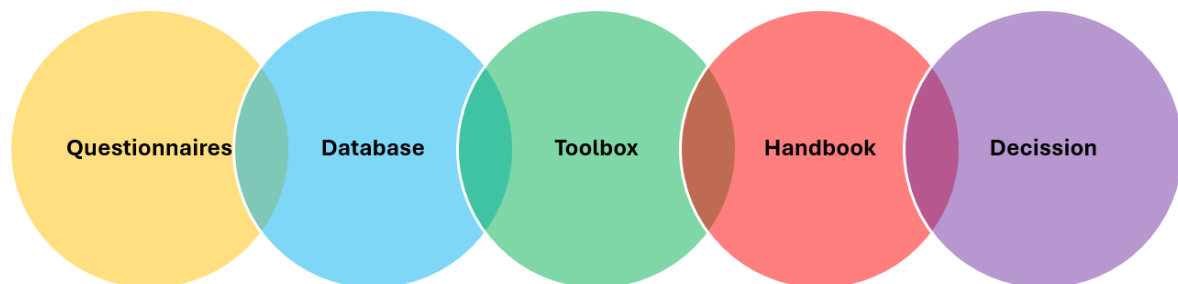
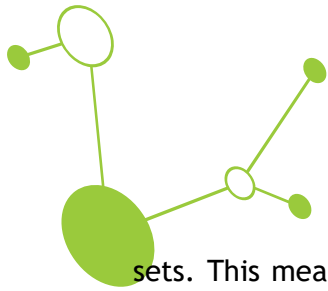


Figure 5. Diagram showing multi-level management of degraded land as a tool developed within the framework of the PoLaRecCE Project

Questionnaires

Within the PoLaRecCE project a survey was conducted to identify and assess principal risks associated with degraded agricultural soils in Central European region. The survey addressed 18 categories of soil degradation, ranging from contamination by industrial emissions and waste disposal to natural processes such as erosion and flooding. The primary target group comprised municipalities, specifically mayors and technical offices responsible for local planning and land management. Their responses provided essential insights into the perception and prioritization of soil degradation issues at the local level. The information obtained via applied survey are of great importance not only from the local perspective (municipality) but may also support strategic planning at the regional scale (marshal's office). As indicated by the survey conducted within the Polish territory the local authorities are not able to sufficiently recognize local environmental problems due to poor environmental monitoring system and limited access to appropriate data



sets. This means that future strategic interventions should concentrate on improvement of this component.

Database

This tool has been developed in order to perform cross-regional comparison of the data obtained via survey (questionnaires) (Figure 6):

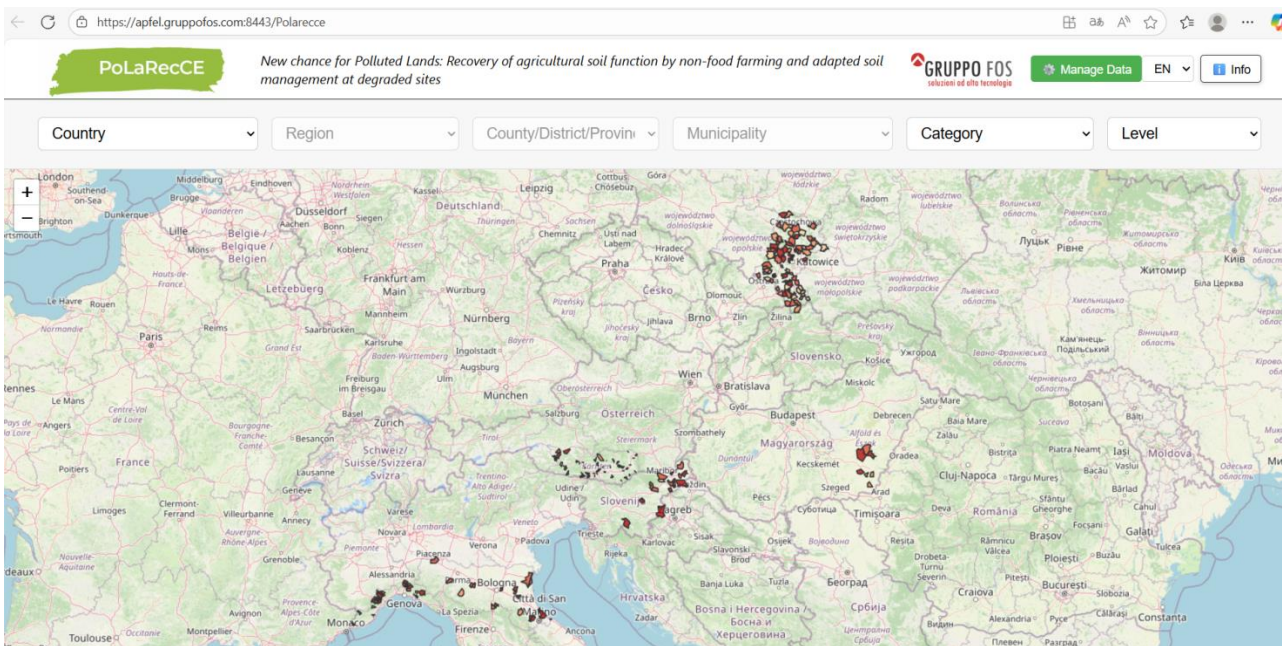
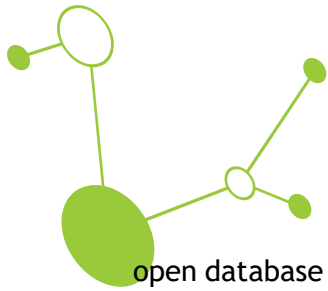


Figure 6. Map of the Central European region, showing municipalities contributing to the database on land degradation

Such an approach allows for the identification of continuous patterns as well as region-specific issues. While some forms of soil degradation appear consistently across Central Europe, others are strongly localized, reflecting differences in geography, industrial history, agricultural intensity, and data availability. This provides an overview of the local and regional issues related to soil degradation, which can be handled directly by local authorities (localized matters), as well as EU commission if specific degradation problems extends beyond country borders. In order to introduce



open database to Polish authorities, IEE PAS organized a one day workshop for stakeholders on 17th December 2025 in Zabrze, Poland.

Through constructing of an open database PoLaRecCE project supports various EU initiatives e.g. designing of EU digital soil health data portal, which will function as a hub providing access to soil data coming from various sources; upgrading the existing EU Soil Observatory; supporting European strategy for data, which focus on developing sector-specific data spaces (e.g. green deal) to pool, access, and share data among different staholders and end-users (Figure 7).

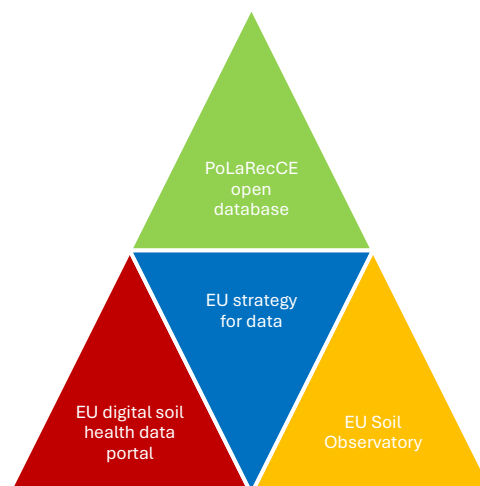
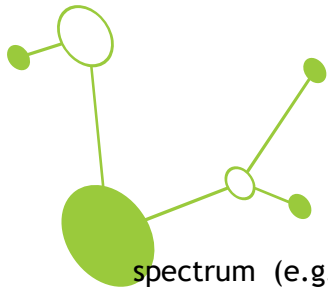


Figure 7. Diagram showing the EU initiatives supporting open access to digital information about the land degradation and soil quality

Toolbox

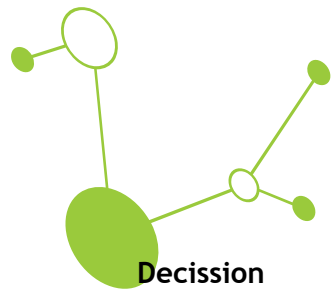
As mentioned before some of the Polish administrative bodies have poor or no access to the data tackling local environmental problems. This is partly related to the periodic soil monitoring campaigns (performed by the regional authorities e.g. Regional Inspectorate for Environmental Protection in the frame of State Environmental Monitoring) designed to recognize contamination issues mainly at the regional or country scale. Moreover, the applied soil quality indicators as well as soil monitoring techniques are generally concentrated on agriculture lands, creating significant challenges to detect and evaluate the range of certain soil contamination problems at the broader



spectrum (e.g. deposition of air pollutants, illegal disposal of wastes) and full scale (e.g. harmonized soil monitoring system applied also in forest, urban and recreational areas). To solve this problem PoLaRecCE project involves application of a set of innovative techniques (toolbox), which can be used to characterize certain physical and chemical properties of degraded soils, considering at the same time multiple pollution sources. The main advantage of the toolbox is that it includes mainly inexpensive and easy to apply procedures, which can be rapidly and effectively used to detect various soil contaminants in diverse areas. Additionally, the toolbox concentrates on ISO (International Organization for Standardization) standardized methods (e.g. ISO 21226:2019), which is in line with the Soil Monitoring Law (EU Directive 2025/2360), which underlines that future soil monitoring initiatives should include methodologies for soil testing that are certified by internationally recognized bodies e.g. ISO and the European Committee for Standardization (CEN).

Handbook

The final tool (handbook) developed during the PoLaReCE project is a primary document intended for the local and regional officials including decision makers responsible for soil management practices. It will contain a full description of the tools designed during implementation of the PoLaReCE project (questionnaires, database and toolbox). Furthermore, it will provide criteria for selecting the best possible revitalization procedure as well as detailed instructions on how to perform the cost-benefit analysis for selected investment options. Pilot sites selected for the purpose of handling different soil degradation types will provide a robust example to stakeholders on how to effectively process and manage lands affected by various pollution sources. In the case of Skawina pilot site certain plant species were considered: giant miscanthus (*Miscanthus × giganteus*), blue spruce (*Picea pungens*), energy poplar (*Populus* spp.) and bamboo (*Phyllostachys* spp.). After thorough environmental and socio-economic analysis performed within the PoLaRecCE project, and series of discussions with Skawina authorities, Miscanthus has been selected for the Polish pilot site. The Miscanthus plantation will serve as a demonstration site for local communities to show how degradation issues can be handled in sustainable manner, supporting at the same time municipality's strategic development plans focusing on ecological restoration, renewable energy, and long-term land management.



All four tools (questionnaires, database, toolbox and handbook) support Polish authorities to find answers to three major questions:

- What are the main soil degradation problems to be solved by our municipality?
- Do they affect only our local area or is it a regional problem?
- What measures can be applied to restore the degraded areas?

With the help of PoLaRecCE tools the strategic planning legislation at the municipality, regional and EU-level will be more harmonized, triggering more rapid revitalization of the degraded areas and initiating “healthy soil” procedures more effectively protecting the unique soil environment.