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Full Length Article

# Phytoremediation as urban regeneration strategy: A framework for sustainable land reclamation in the Milan Metropolitan Area

Maria Chiara Pastore[a,d,*], Claudia Ida Maria Parenti[a], Laura Sibani[d,e], Lucia Ludovici[b,d], Massimo Labra[c,d], Werther Guidi Nissim[c,d]

[a] Department of Architecture and Urban Studies, Polytechnic University of Milan, Milan 20133, Italy
[b] Department of Electronic, Information and Bioengineering, Polytechnic University of Milan, Milan 20133, Italy
[c] Department of Biotechnology and Biosciences, University of Milano-Bicocca, Milan 20126, Italy
[d] National Biodiversity Future Center (NBFC), Palermo 90133, Italy
[e] Department of Earth and Sea Sciences, University of Palermo, Palermo 90123, Italy

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ABSTRACT

Urban brownfields and degraded areas pose pressing environmental and social challenges, especially in metropolitan contexts shaped by industrial legacies and land-use transformations. Among the nature-based solutions available, phytoremediation, using plants to mitigate soil contamination, offers a sustainable, low-impact alternative to conventional reclamation techniques. Despite its ecological benefits, phytoremediation remains underused in urban planning due to uncertainties and long treatment times. This study applied a GIS-based multi criteria analysis integrating open source spatial data, soil parameters, and satellite image interpretation to identify suitable areas for phytoremediation within the Milan Metropolitan Area (MMA). A weighted evaluation framework was developed by considering soil characteristics (texture and organic carbon content), vegetation cover, site size, and total available free surface (areas not occupied by built structures) to calculate suitability indices. Results show that out of 720 mapped sites, approximately 40 % displayed good or high suitability for phytoremediation, highlighting important opportunities for sustainable soil regeneration within the urban fabric. Integrating environmental planning and landscape design perspectives, the findings support a broader vision of sustainable urban transformation and demonstrate how soil regeneration can play a critical role in shaping future green infrastructure and ecological networks.

## 1. Introduction

The current Anthropocene epoch (Crutzen and Stoermer, 2021) is characterized by the profound and far-reaching impacts of human activity on the planet. Among the many consequences of this era, soil degradation has emerged as one of the most critical environmental challenges, as soil is a non-renewable resource that underpins essential ecological functions vital to sustaining life on Earth. The need for soil preservation and regeneration is increasingly recognized across international, European, and national environmental policies and strategies (Heuser, 2022). Within this context, the regeneration of polluted or abandoned sites resulting from urban expansion and anthropogenic activity has become a central challenge for contemporary urban planning (Hollander et al., 2010; Losco and de Biase, 2021). These degraded spaces—marked by contamination, neglect, and disuse—represent the material legacy of past industrial and production models, and are now often excluded from the functional urban system (O'Callaghan and Di Feliciantonio, 2023; Rey et al., 2022). Their persistence has reshaped contemporary urban landscapes, generating vast voids within densely built-up areas and/or leaving behind fragmented residual spaces in peri-urban contexts (López-Piñeiro, 2020). The persistence of these spaces is largely attributable to the high costs, technical challenges, and administrative complexities associated with their reclamation (Ingaramo et al., 2022).

Yet, they also embody a latent ecological and cultural potential. Often described as "terrain vague" (De Solà-Morales, 1995), these sites convey both absence and possibility: their marginal and indeterminate nature allows spontaneous ecological processes to unfold and

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* Corresponding author at: Department of Architecture and Urban Studies, Polytechnic University of Milan, Milan, 20133, Italy.
*E-mail address:* mariachiara.pastore@polimi.it (M.C. Pastore).

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encourages new forms of public imagination. Their emptiness—marked by the absence of formal planning—holds a promise of renewal, where the "void" can become a living laboratory for urban biodiversity and landscape experimentation. These reflections align with the ecoterritorialist perspective (Magnaghi and Marzocca, 2023), which advocates a paradigm shift in the approach to urban regeneration. From this standpoint, the recovery of degraded areas should not be limited to their economic reintegration but instead framed as part of a broader territorial strategy aimed at ecological restoration, community engagement, and landscape requalification. Degraded spaces, therefore, should not be regarded as residual wastelands but as potential nodes within a renewed ecological infrastructure, capable of reconnecting natural and urban systems.

The issue of urban degradation is not confined to a single geographical context but represents a widespread global challenge, as demonstrated by studies on post-socialist cities (Petaccia and Angrilli, 2020). Brownfield sites—particularly in Europe, North America, and China—have become a major focus of research and policy initiatives aimed at curbing urban sprawl, reintegrating degraded land, and enhancing ecosystem services (Zheng and Masrabaye, 2023). Recent bibliometric analyses reveal a growing body of literature integrating remediation, biodiversity restoration, and spatial planning, with a particular emphasis on the ecological potential of these neglected urban landscapes. From a planning perspective, brownfield reuse has become a key priority for preventing further urban expansion into greenfield sites and limiting overall land consumption. As already impermeabilized surfaces, these areas offer a strategic opportunity to counteract soil sealing and restore urban biodiversity through integrated interventions combining remediation, depaving, and ecological restoration (Anderson and Minor, 2017; Caselli et al., 2024). For this reason, the regeneration of brownfields has become a central component of European strategies aimed at addressing land degradation and pollution (European Commission, 2021).

Across Europe, more than two million contaminated sites have been identified by the European Environment Agency—a figure that highlights the urgency of coordinated and scalable action. The recently adopted *Nature Restoration Regulation* (European Parliament and Council, 2024) explicitly includes urban and peri-urban environments among its restoration targets, emphasizing the need to tackle ecological degradation within the built environment. In Italy, the scale of the problem is similarly significant. According to the latest report by the Italian Institute for Environmental Protection and Research (ISPRA, 2023), more than 35,000 sites were subject to remediation procedures in 2020, nearly half of which (46 %) are still ongoing. Many of these cases remain stalled due to the type, extent, and severity of contamination, the high costs of remediation, or other administrative constraints.

Remediation is generally undertaken in response to urgent public health risks or as part of urban redevelopment processes, which are more likely to occur in economically attractive areas (Longo and Campbell, 2017). The most widespread reclamation techniques involve soil excavation and landfilling—methods that are fast but costly and environmentally detrimental (Hou et al., 2018)—or highly engineered approaches such as soil vapor extraction, soil flushing, electrokinetics, vitrification, and solidification/stabilization. The escalating costs and technical complexity of conventional remediation methods have underscored the need for alternative approaches to soil reclamation—ones that integrate environmental remediation with landscape and urban design (Robiglio et al., 2014).

Among these alternative approaches, phytoremediation has attracted increasing attention, as it not only contributes to soil regeneration but also enhances biodiversity within urban environments (Song et al., 2019). This technique relies on plants and their associated microorganisms to absorb, degrade, or stabilize contaminants, offering a sustainable and low-impact strategy for soil reclamation (Shmaefsky, 2020). Compared with most conventional remediation techniques, phytoremediation is less invasive, more cost-effective, and capable of generating multiple co-benefits, such as improving biodiversity, enhancing soil health, and creating new urban green spaces. The establishment of new urban green spaces provides ecological as well as social benefits, offering habitats for biodiversity while also creating accessible spaces for recreation (Petrova et al., 2022; Sleegers, 2010). The ability of phytoremediation to integrate ecological, aesthetic, and social dimensions makes it particularly suitable for urban and peri-urban contexts, where environmental rehabilitation can be combined with community use and social interaction.

The growing number of experimental projects and policy strategies implementing phytoremediation as a sustainable solution for reclaiming polluted urban sites demonstrates that it is an increasingly active and promising field of research (Cundy et al., 2016; Fernández-Braña et al., 2023; Newton et al., 2023). However, its long timeframes, variable outcomes, and uncertain efficiency continue to discourage public administrations and private developers from adopting this technology in contexts with strict temporal or functional constraints. The inherent uncertainty surrounding its results also hampers large-scale implementation, limiting its diffusion in urban practice. Moreover, the identification of suitable sites for phytoremediation remains complex, as it requires consideration of soil characteristics, contamination typologies, and planning constraints, together with the willingness of property owners and local authorities to engage in long-term ecological experimentation. At the municipal level, several pilot initiatives have begun to address these challenges by scaling up phytoremediation from isolated site-specific interventions to broader territorial frameworks (Bruxelles Environnement et al., 2024; UIA Urban Innovation Act, 2024). Few studies, however, have systematically examined how to identify and prioritize suitable sites for phytoremediation within urban contexts (Chatterjee, 2023), including the use of emerging technologies such as satellite imagery to detect contamination (Torres and Fraternali, 2021).

Against this backdrop, the present research develops a scalable, GIS-based framework designed to identify areas suitable for phytoremediation within the Milan Metropolitan Area (MMA). The model integrates ecological, botanical, and planning criteria to evaluate the potential of degraded sites for soil regeneration. Milan represents a particularly relevant case study, as it is one of Italy's most industrialized regions, where numerous abandoned sites still bear the legacy of industrial and vehicular contamination. By combining multiple datasets and indicators, the proposed framework enables the differentiation of sites according to their physical, ecological, and management characteristics, resulting in the definition of suitability indices and intervention priorities. The overarching objective of this study is to support local authorities and urban planners in identifying areas where phytoremediation can promote soil recovery, enhance ecological connectivity, and reactivate neglected urban spaces. Beyond its local application, the framework contributes to a broader discussion on how nature-based remediation strategies can be embedded within urban planning and design tools to foster resilience and ecological regeneration in metropolitan environments.

## 2. Materials and methods

This research presents a methodological framework for identifying and evaluating areas suitable for phytoremediation within the Milan Metropolitan Area (MMA). The workflow integrates spatial mapping and modeling with soil regeneration strategies, combining environmental, spatial, and planning data through a GIS-based multi-criteria approach. The method is structured in three consecutive phases: (1) construction of a comprehensive database; (2) multi-criteria evaluation of phytoremediation suitability; and (3) identification of priority areas for intervention. The overall research framework is illustrated in Fig. 1. It connects the conceptual and analytical components of the study, linking the theoretical definition of the research aims with the practical

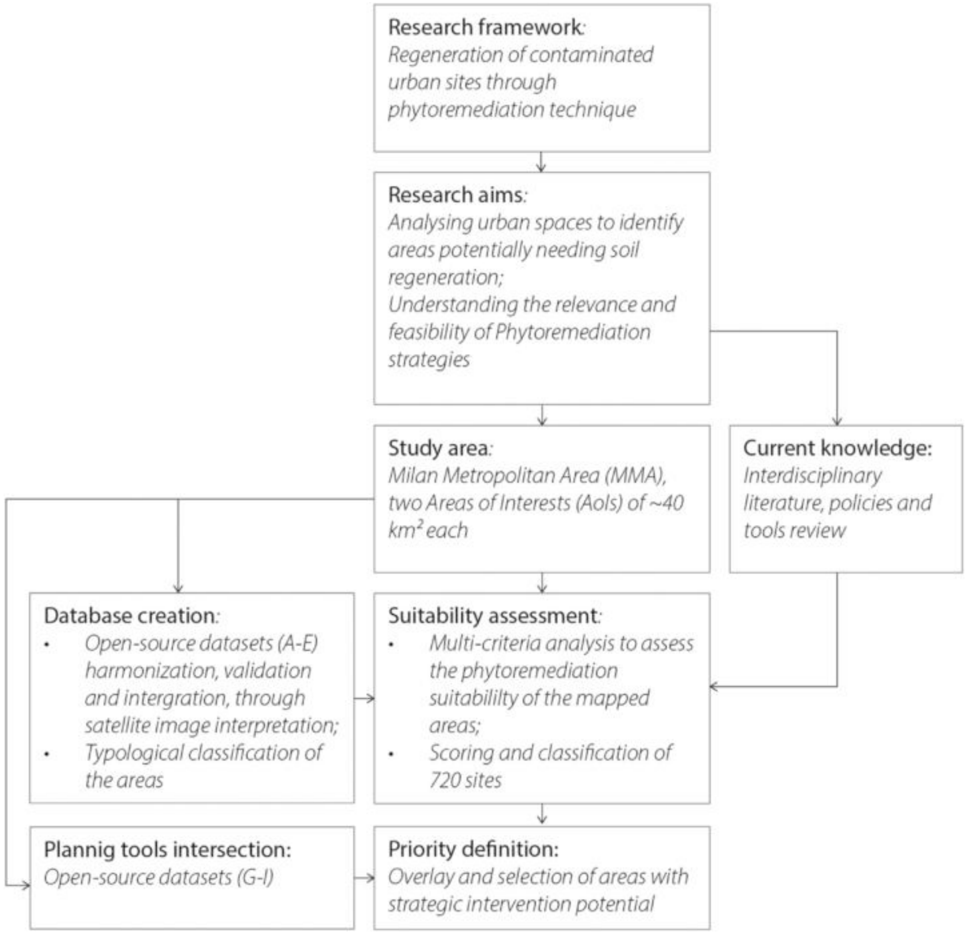


**Fig. 1.** Research framework illustrating the conceptual steps of the study, from the definition of the research aim to the prioritization of phytoremediation sites in the Milan Metropolitan Area.

implementation of spatial analysis tools. The diagram outlines the logical sequence of activities: reviewing the current state of knowledge; identifying degraded and contaminated areas through database harmonization; assessing their suitability for phytoremediation; and, finally, intersecting these results with planning instruments to define strategic intervention priorities. This structure was designed to ensure both replicability and scalability, allowing the methodology to be applied to other metropolitan contexts affected by comparable patterns of soil degradation and urban transformation.

The study specifically addresses the following research questions: (RQ1) Which areas potentially requiring soil regeneration can be identified in existing open-source datasets, and how can these datasets be integrated, consolidated, and expanded—through satellite image interpretation—into a comprehensive database supporting strategic interventions? (RQ2) Which degraded sites exhibit suitable conditions for phytoremediation based on multi-criteria spatial analysis? (RQ3) Which sites should be prioritized for remediation actions?

Building on this conceptual model, the complete analytical workflow is presented in Fig. 2, which visually summarizes each operational step of the process—from the definition of the study areas to the final prioritization of intervention sites. Fig. 2 illustrates how the study progresses through four interconnected stages: (1) Definition of the study area, including the selection of two areas of interest (AoIs) within the Milan Metropolitan Area; (2) Creation of the soil regeneration database, based on the harmonization of open-source spatial datasets (A–E) and the integration of satellite-image interpretation to validate and refine the mapping of degraded sites; (3) Evaluation of phytoremediation suitability, conducted through a multi-criteria analysis using five weighted variables (free soil, vegetation cover, soil texture, soil carbon content, and site size) and a six-class scoring system; (4) Prioritization of intervention areas, achieved through spatial overlay with additional planning datasets (G–I), to identify those sites that combine high suitability with policy relevance. This figure therefore provides a detailed representation of the methodological logic and data flow, ensuring both the clarity and replicability of the analytical process.

### 2.1. Description of the study area

The analysis was conducted within the Milan Metropolitan Area (MMA), located in the Lombardy region of northern Italy. As one of the country's most historically industrialized territories, the processes of deindustrialization and the rise of the tertiary sector have profoundly reshaped its urban structure over recent decades (Pinto, 2010). The regeneration of sites left behind by industrial decline—particularly within the city of Milan—has triggered major redevelopment initiatives and the redesign of entire districts (Mocarelli, 2020). The reuse of some of these former industrial sites remains at the centre of ongoing public debate. Beyond these large-scale redevelopment areas, however, the MMA also includes a substantial number of smaller sites resulting from urban sprawl and agricultural abandonment. These areas, degraded by past human activities, are often characterized by neglect and environmental compromise. As the territory has undergone economic transformation and become increasingly attractive, urban regeneration has emerged as a central theme in local planning agendas. This topic has been addressed at the provincial level through the *Territorial Metropolitan Plan* (2021), which in 2024 established *Strategy No. 1: Sustainability, Environment, and Regeneration.*

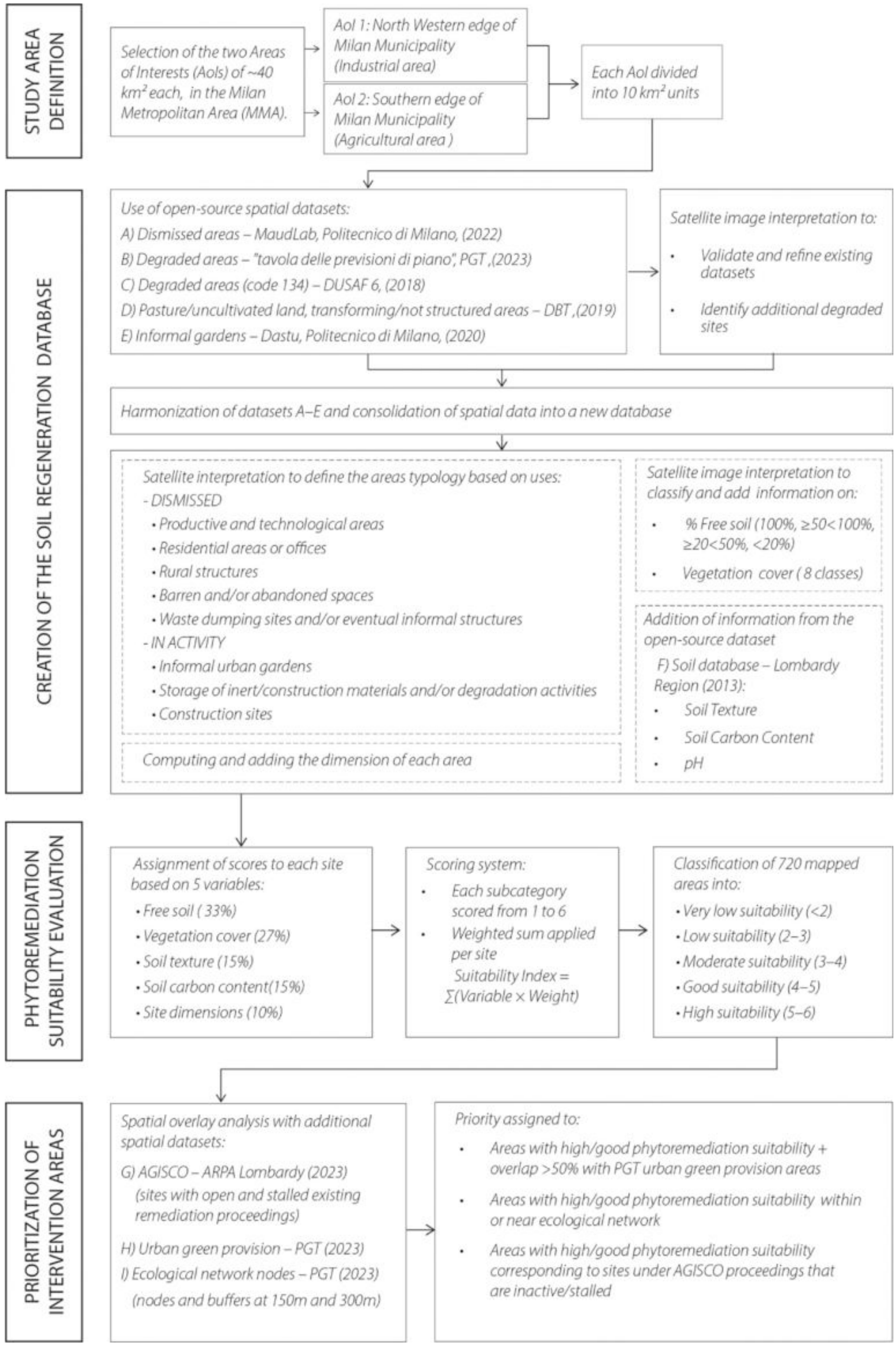


**Fig. 2.** Overview of the methodological workflow used to identify, evaluate, and prioritize phytoremediation-suitable sites across the Milan Metropolitan Area.

In parallel, growing attention has been devoted to green infrastructure planning, most notably through the *Forestami* project (2018), which aims to expand tree canopy cover and foster biodiversity across the metropolitan area (Pastore, 2025). Within this context of increasing interest in urban regeneration and environmental planning, soil degradation stands out as a key challenge. These degraded areas represent potential sites for phytoremediation applications, offering opportunities to explore innovative soil regeneration strategies. The Lombardy Region's *Urban Regeneration Law* (Regione Lombardia, 2019), which promotes sustainable development practices and addresses ecological and environmental degradation, underscores the City of Milan's commitment to soil restoration. Within this regulatory framework, phytoremediation has been recognized as an innovative and sustainable approach to soil rehabilitation and is explicitly referenced in the *Territorial Government Plan* (*Piano di Governo del Territorio*, *PGT*, Art. 7, paragraph 4) as a potential strategy for effective remediation.

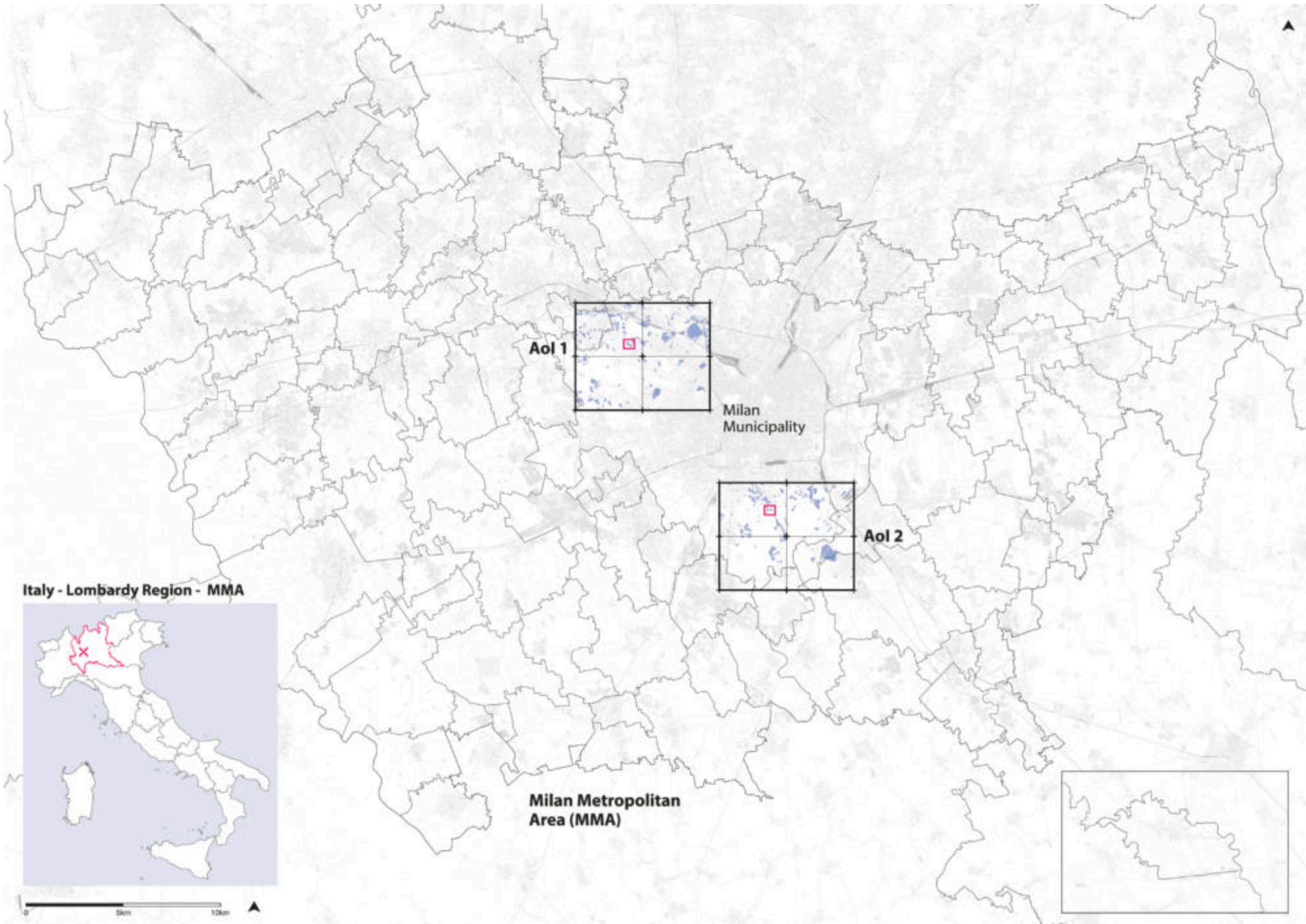


**Fig. 3.** The study areas: Milan Metropolitan Area and the two AoIs. On the left-hand side, the key map of Italy indicates the location of Lombardy and the Milan Metropolitan Area (MMA).

For this study, two areas of interest (AoIs) were selected along the municipal border of Milan (Fig. 3), each covering approximately 40 $km^2$ and subdivided into 10 $km^2$ sectors. These areas were chosen because the mapping and spatial analysis were conducted at a high level of detail that could not be extended to the entire metropolitan area. The two AoIs were delineated by enlarging the spatial context around two already recognized contaminated sites. Both sites are officially listed among the areas undergoing reclamation procedures, are affected by contamination, and have been identified by the Municipality of Milan as priorities for regeneration. The two AoIs have also been considered as they represent markedly different contexts. The first, located on the northwestern edge of the city, is characterized by a higher density of industrial activities and a greater degree of urbanization. In contrast, the second area, situated within the *Parco Agricolo Sud*, consists predominantly of extensive agricultural land. This differentiation made it possible to conduct a comprehensive assessment of soil conditions and remediation strategies across diverse urban and peri-urban settings.

### 2.2. Open-source data for brownfield identification

The initial phase of the research involved a territorial analysis aimed at identifying sites with potentially degraded soils. The study relied on open-access and institutional geospatial datasets provided by regional and metropolitan authorities (Table 1), as well as on satellite image interpretation, to evaluate and map areas affected by potential soil degradation.

Databases A to E provided information on soil conditions, including indicators of land degradation and decommissioned areas, as well as data on land uses and activities potentially contributing to soil deterioration. Database F contained information on the main functional characteristics of the soil—such as average carbon content, pH, and texture—which were particularly relevant to the objectives of this research. Databases G, H, and I offered additional datasets used to assess intervention priorities. These data were derived from the *Register of Contaminated Sites (AGISCO)* and *Territorial Government Plan (PGT)* databases. The AGISCO database serves as the Lombardy Regional Register of Sites Under Contamination Management Procedures and contains essential information about ongoing or completed reclamation processes. It includes vector data—both point and polygon features—and a document listing site-specific contaminants. However, the database is only partially complete: polygon data and contaminant lists are available for only a subset of the recorded cases. The *Territorial Government Plan (PGT)* database, on the other hand, provides spatial data, among others, on urban green areas and ecological networks, which are essential for understanding the spatial distribution and quality of green infrastructure within the city. This dataset was particularly important for evaluating the current state of urban green spaces and for identifying areas suitable for ecological enhancement and improved connectivity among the city's green areas.

### 2.3. Implementing a database for "soil regeneration areas"

Based on the integrated datasets collected, the next step consisted of constructing a new database aimed at identifying areas requiring soil regeneration within the two AoIs. This process involved the integration of existing spatial datasets (i.e., A to E) with additional information specifically mapped for the research objectives.

**Table 1**
Databases used for the study.

| Database | | Source |
|---|---|---|
| A | Dismissed areas | Politecnico di Milano, MaudLab, 2022 |
| B | Degraded areas | *Territorial Government Plan* (*PGT*), "tavola delle previsioni di piano", 2023 |
| C | Degraded areas, non-vegetated and unused (code 134) | Destination of use of agricultural and forestry soils (DUSAF 6), 2018 |
| D | Pasture/uncultivated land; areas under transformation | Topographic database (DBT), 2019 |
| E | Informal gardens: gardens with unknown owners | "Mappatura orti urbani nella Città metropolitana di Milano", Politecnico di Milano, Dastu, 2020 |
| F | Soil database | Lombardy Region, 2013 |
| G | Register of Contaminated Sites (AGISCO) | Lombardy Regional Environmental Protection Agency (ARPA), 2023 |
| H | Urban green provision | *Territorial Government Plan (PGT)*, "tavola delle previsioni di piano", 2023 |
| I | Ecological network nodes | *Territorial Government Plan (PGT)*, "tavola delle previsioni di piano", 2023 |

The first phase involved harmonizing these datasets by standardizing their attribute tables. This procedure was essential to integrate data originating from different sources—each with its own format and level of detail—and to ensure overall consistency while avoiding the loss of relevant information. Once harmonized, the datasets were consolidated, and a legend defining the key characteristics of the study area was developed.

The resulting database was organized around two main thematic categories: (1) Dismissed sites, including industrial, infrastructural, or productive areas that are no longer in use or have been abandoned; (2) Inactivity sites, including areas with current or past uses that may have contributed to soil degradation. This initial distinction was fundamental to improving the understanding of site conditions and potential future development trajectories. These two categories were then subdivided into specific subtypes, which were mapped through satellite image interpretation or extracted from the initial datasets.

The method used to construct the legend and categorize the data is illustrated in Fig. 4, which shows satellite examples of the site typologies, and in Table 2, which presents the step-by-step process used to define the legend.

The identified categories are as follows: (1) "Productive and technological areas", "residential areas or offices", and "rural structures"—these categories primarily derive from the *Dismissed Areas* dataset (2022), excluding sites that have already been transformed, as verified through satellite image interpretation. Since this dataset was originally developed for the regional landscape plan, the included sites are expected to undergo future interventions for reclamation or reuse within broader landscape rehabilitation strategies. During the mapping phase, additional areas were incorporated based on their characteristics—such as location within industrial or manufacturing zones, or the type of built structures and settlement patterns—which align with this classification. These spaces are generally characterized by the presence of existing buildings or demolition remnants, offering potential for mixed-use regeneration projects.

(2) "Barren and/or abandoned spaces"—This typology refers to vacant or partially developed lots in urban contexts and to uncultivated lands in agricultural settings. Such spaces often result from dispersed urbanization or from leftover areas associated with infrastructure, typically inaccessible to citizens. Due to neglect, they are frequently characterized by spontaneous renaturalization processes and irregular maintenance, while in some cases they host illegal activities such as sporadic dumping.

(3) "Waste dumping sites and/or informal structures"—These are areas where waste materials have been consistently and illegally dumped. In some instances, they also contain buildings or structures erected without authorization and now in a state of decay, posing risks to public health and safety.

(4) "Informal urban gardens"—identified through the Politecnico di Milano mapping project (Cucchi et al., 2020)—are sites where private citizens have appropriated public or private land to cultivate fenced plots for horticultural purposes, either for personal consumption or informal sales, without proper authorization. Such spaces may be affected by the excessive use of pesticides, fertilizers, or other chemicals, leading to soil and water contamination and posing health risks for nearby residents and workers. Typically located along infrastructure corridors, near water bodies, or within enclosed areas, these gardens often occupy land owned by public institutions or private entities. Although they may enhance the surrounding environment and promote community well-being, their transformation poses complex challenges. Effective redevelopment requires the involvement of local communities managing these spaces to ensure a smooth transition and to prevent conflicts between citizens and governing authorities.

(5) Storage of inert/construction materials and/or degrading activities—This category includes areas used for storing construction materials such as bricks, cement, sand, and other building supplies. It also encompasses sites where formal or informal commercial activities take place that may cause environmental degradation—for example, junkyards or scrapyards used for the collection and sale of scrap metal, vehicles, or other materials. These areas are often situated along the edge of agricultural land, forming a transitional belt between urban and rural zones. This peri-urban interface is typically characterized by fragmented and degraded landscapes.

(6) Construction sites—These areas are currently undergoing development processes with uncertain duration, where soil quality may be temporarily or permanently affected by construction activities.

The creation of the "Soil Regeneration Areas" database involved a meticulous process of satellite imagery analysis and interpretation. This step was crucial for identifying and mapping specific scenarios corresponding to the typologies described above. Satellite images were carefully examined to detect spatial patterns, physical features, and surface conditions indicative of the different categories, while also verifying the accuracy of the existing datasets.

In addition to integrating and updating information derived from satellite imagery, considerable effort was dedicated to refining and harmonizing Databases A to E. This was necessary due to discrepancies in the year of update among the datasets, as well as inconsistencies between their recorded data and the current on-ground conditions. Accordingly, the study built upon open data sources, systematically validating their reliability to minimize the potential margin of error.

Alongside the identification of typologies, satellite image interpretation was also used to determine the percentage of "free soil" and "vegetation cover". "Free soil"—defined as land not occupied by buildings or other impermeable structures—was classified into four categories: (1) completely free (100 %); (2) moderately built (50 %–99 % free); (3) highly built (20 %–49 % free); and (4) predominantly built ( < 20 % free). The areas most relevant to this study fall within the first two categories, where demolition is unnecessary or limited, thus requiring fewer interventions and lower costs for implementing phytoremediation.

"Vegetation cover", an essential indicator for assessing site suitability for phytoremediation, was also classified through satellite image interpretation. Eight categories were defined: (1) urban gardens; (2) meadow; (3) meadow with sparse tree clusters; (4) mixed meadow/shrubland/wood; (5) mixed meadow/shrubland/wood with paved or


**Fig. 4.** Examples of typologies identified through satellite image interpretation.

compacted soil areas; (6) paved or compacted soil areas with mixed meadow/shrubland/wood patches; (7) absent—paved; and (8) absent—compacted soil.

Finally, information on soil characteristics from "Database F (Soil Data)"—including carbon content, pH, and texture—was incorporated to complete and enhance the analytical framework.

### 2.4. Evaluating soil regeneration suitability

To assess which sites were most suitable for phytoremediation, a set of evaluation criteria was established, as visible in Table 3. The first step involved analysing the various sub-classes of interest and assigning them scores ranging from 1 to 6, with 6 indicating optimal conditions for the implementation of phytoremediation.

Subsequently, a weighted-sum analysis was performed according to the following formula:

$$W_{\text{sum}} = \sum_{i=1}^{n} V_i W_i$$

where $V$ represents the variable and $W$ the corresponding weight.

The percentage weights express the relative importance of each variable in the overall suitability evaluation, while the scores (1–6)

**Table 2**
Construction of the legend.

| Theme | Typology | Source data: original/categories |
|---|---|---|
| Dismissed | Productive or technological areas | Database A: productive, technology–mobility–infrastructures;<br>Survey based on satellite images* |
| | Residential areas or offices | Database A: residential, administrative services, public services, historical buildings, commercial;<br>Survey based on satellite images* |
| | Rural structures | Database A: agricultural;<br>Survey based on satellite images* |
| | Barren and/or abandoned spaces | Database A: open areas, other;<br>Database B: degrade areas;<br>Database C: degraded areas, non-vegetated and unused;<br>Database D: pasture/uncultivated, transforming/not structured areas;<br>Survey based on satellite images* |
| | Waste dumping sites and/or eventual informal structures | Survey based on satellite images* |
| Inactivity | Storage of inert/building materials and/or degradational activities | Survey based on satellite image* |
| | Informal urban gardens | Database E: not available, not found;<br>Survey based on satellite images* |
| | Construction sites | Survey based on satellite image* |

Note: * denote each geometry could originate from datasets A, B, C, D, or E—possibly modified following satellite data interpretation—or represent a new geometry, not included in any of the original datasets, and mapped directly through satellite image analysis.

**Table 3**
Variables and weights for evaluation.

| Variables | Weights (%) | Sub-categories | Weights |
|---|---|---|---|
| Free soil | 33 | 100 % | 6 |
| | | 50 %–99 % | 5 |
| | | 20 %–49 % | 2 |
| | | $<$ 20 % | 1 |
| Vegetation cover | 27 | Meadow/urban gardens | 6 |
| | | Meadow with sparse groups of trees | 5 |
| | | Mix of meadow/shrubland/wood | 4 |
| | | Mix of meadow/shrubland/wood and paved/soil compacted areas | 3 |
| | | Paved/soil compacted areas and mix of meadow/shrubland/wood | 2 |
| | | Absent-paved / Absent-compacted soil | 1 |
| Soil texture | 15 | Loamy | 6 |
| | | Loamy-silty | 5 |
| | | Loamy-sandy | 4 |
| | | Loamy-clayey | 3 |
| | | Sandy | 2 |
| | | Clayey | 1 |
| Soil carbon content | 15 | $\geq 5$ | 6 |
| | | $\geq 2$ and $< 5$ | 5 |
| | | $\geq 1.5$ and $< 2$ | 4 |
| | | $\geq 1$ and $< 1.5$ | 3 |
| | | $\geq 0.5$ and $< 1$ | 2 |
| | | $< 0.5$ | 1 |
| Site dimensions | 10 | $> 15{,}000\ m^2$ | 6 |
| | | $\geq 1000\ m^2$ and $\leq 3000\ m^2$ | 5 |
| | | $> 3000\ m^2$ and $\leq 6000\ m^2$ | 4 |
| | | $> 6000\ m^2$ and $\leq 10{,}000\ m^2$ | 3 |
| | | $> 10{,}000\ m^2$ and $\leq 15{,}000\ m^2$ | 2 |
| | | $< 1000\ m^2$ | 1 |

assigned to each sub-category indicate the degree of suitability for phytoremediation. The final suitability index integrates these two components through the weighted-sum method, enabling a transparent, quantitative, and reproducible assessment of site potential.

The weighting of each variable was determined through an interdisciplinary evaluation carried out together with botanists and agronomists from the University of Milano-Bicocca, partners of the overall research, and supported by an extensive review of the scientific literature on phytoremediation and soil suitability.

The “free soil” parameter received the highest weight (33 %) since the amount of available, unbuilt surface within each plot was considered a key factor in the evaluation. The absence of buildings increases the potential for phytoremediation by reducing the need for demolition and associated operational costs.

The “vegetation cover” variable was assigned a weight of 27 %. Grasslands and areas used as urban gardens were prioritized as the most cost-effective conditions for phytoremediation, whereas paved or compacted surfaces pose challenges for plant establishment and growth. Such surfaces require costly preparatory operations (e.g., excavation or soil loosening), substantially increasing the overall implementation costs.

The "soil texture" variable was weighted at 15 %. The ideal texture for phytoremediation is loamy, offering a balance between water retention and drainage that supports both root growth and microbial activity—processes essential for contaminant uptake and degradation (Sharma et al., 2023; Sharma and Kumar, 2023). By contrast, sandy soils with high percolation rates and clay soils with poor drainage are less suitable, as they can lead to contaminant leaching or waterlogging, hindering plant survival. In the present study, the loamy class was used for evaluation, as neither sandy nor clayey textures (nor their subcategories) are present within the analysed areas.

The "soil carbon content" parameter was also assigned a weight of 15 %, reflecting its critical role in supporting microbial life, soil fertility, and plant growth (Gerke, 2022). A higher carbon content typically indicates healthier soil with greater nutrient availability, improved water retention, and enhanced microbial activity—all favourable conditions for effective phytoremediation.

Finally, the "site dimension" variable received the lowest weight (10 %). Although site size is a relevant factor for the feasibility of phytoremediation, it entails considerations that can sometimes conflict. From an agronomic perspective, larger plots are operationally advantageous, as they allow the use of agricultural machinery and reduce labour costs (Van den Berg et al., 200). However, large sites also require more complex planning, face potential regulatory constraints, and involve logistical challenges that may necessitate integrated remediation approaches combining phytoremediation with conventional techniques. Conversely, smaller sites—particularly those ranging between 1000 and 3000 $m^2$—are well suited for pilot phytoremediation projects. Yet, sites smaller than 1000 $m^2$ may face operational difficulties, higher per-unit costs, and limited ecological impact, making them less favourable for large-scale environmental improvement.

### 2.5. Assessing the priority of intervention

After identifying areas with potential for soil regeneration—i.e., sites where contamination is conceivable but not yet confirmed—based on their suitability for phytoremediation, it was necessary to establish additional criteria to prioritize interventions. The initial suitability assessment focused primarily on the intrinsic characteristics of the sites that influence the feasibility and success of phytoremediation projects. However, further contextual factors must be considered to determine which areas present the highest strategic potential for implementation. Therefore, priority was assigned to sites that met one or more of the following conditions: (1) areas currently subject to open remediation procedures that are old enough to be considered stalled; (2) areas designated by the urban plan for existing or planned public green use; and (3) areas located within or in proximity to the city's ecological network nodes.

Phytoremediation is a reclamation technique that requires detailed soil contamination assessments, often involving costly and time-consuming investigations. For this reason, since public administrations typically initiate remediation procedures only under specific legal conditions, priority for phytoremediation was given to sites where such legal proceedings are already underway.

The prioritization process relied on data derived from the databases described in Section 2.2, specifically: (1) the *Register of Contaminated Sites (AGISCO)* database (Database G), used to identify degraded areas overlapping with officially registered contaminated sites; (2) the *Urban Green Provision* database (Database H), which identifies areas designated as "public green" and prioritized for their potential to maintain or enhance green functions after reclamation; and (3) the PGT's *Ecological Network Nodes* database (Database I), which delineates areas located within or adjacent to ecological network nodes that could act as connectors or stepping stones to counteract habitat fragmentation.

A spatial overlay analysis was subsequently performed between the mapped areas and the three prioritization datasets to identify sites that simultaneously met multiple criteria. This operation enabled the ranking of areas according to their strategic value for phytoremediation within the broader urban and ecological context.

## 3. Results and discussion

### 3.1. Soil regeneration suitability results

The first objective of this study was to identify, map, and quantify the areas within the city that are potentially suitable for redevelopment through phytoremediation. The main results are presented in Fig. 5. Overall, areas exhibiting anthropogenic uses or misuses accounted for 6.8 % of the total surface area within the AoIs. Of this 6.8 % of degraded land, nearly 40 % demonstrated good or high potential for effective reclamation through phytoremediation. This result indicates that a considerable proportion of the analysed territory holds significant potential for urban soil regeneration. Specifically, the best-suited areas—combining both good and high suitability classes—corresponded to 331 out of 720 mapped soil regeneration sites (Table 4). Among these, 303 sites were classified as having good suitability, covering 197.46 ha, while 28 sites were categorized as highly suitable, spanning a total of 20.73 ha.

The category of "barren and/or abandoned spaces" dominated both in terms of the number of sites and total available surface area (Table 5). Specifically, these sites represented nearly the entire high suitability class and accounted for a substantial proportion of the good suitability category as well. Although "informal urban gardens" were not classified as highly suitable, the entire category fell within the good suitability range. Considering that these areas may be affected by soil contamination due to the use of fertilizers and agrochemicals, their significant presence within urban contexts suggests a considerable potential for greening and pollution mitigation. Their remediation could therefore contribute to urban sustainability and improve local environmental conditions by transforming contaminated plots into productive green spaces. Furthermore, the classes "productive and technological areas" and "waste dumping sites and/or informal structures" also warrant attention, as they included a notable number of sites categorized as good suitability for phytoremediation. These areas are likely to be significantly contaminated—either due to former industrial activities, the presence of backfilled soils, or the accumulation of waste—which may exacerbate their overall degree of degradation. In such cases, given the likelihood of highly compromised soil conditions, it is essential to carefully assess both the actual extent and severity of contamination and the potential costs of required operations, such as demolition, site cleaning, and soil decompaction, before implementing phytoremediation strategies.

### 3.2. Priority of intervention results

A spatial intersection was performed between the areas previously evaluated for phytoremediation suitability and two additional planning datasets: the *Urban Green Provision* (Database H) and the *Ecological Network Nodes* (Database I) from the *Territorial Government Plan (PGT)* (Fig. 6). This step aimed to assess the proximity and overlap of potential phytoremediation sites with existing or planned green areas and ecological corridors. Although the number of sites fulfilling these additional criteria was limited compared to the total number of suitable sites, this parameterization is essential for determining which areas would most benefit from phytoremediation interventions.

Land reclamation through phytoremediation is particularly significant when the current or future use of a site involves maintaining its green function and vegetation cover (Guidi Nissim et al., 2023). When a site is intended for future construction, phytoremediation is less suitable, as the vegetation established during remediation would

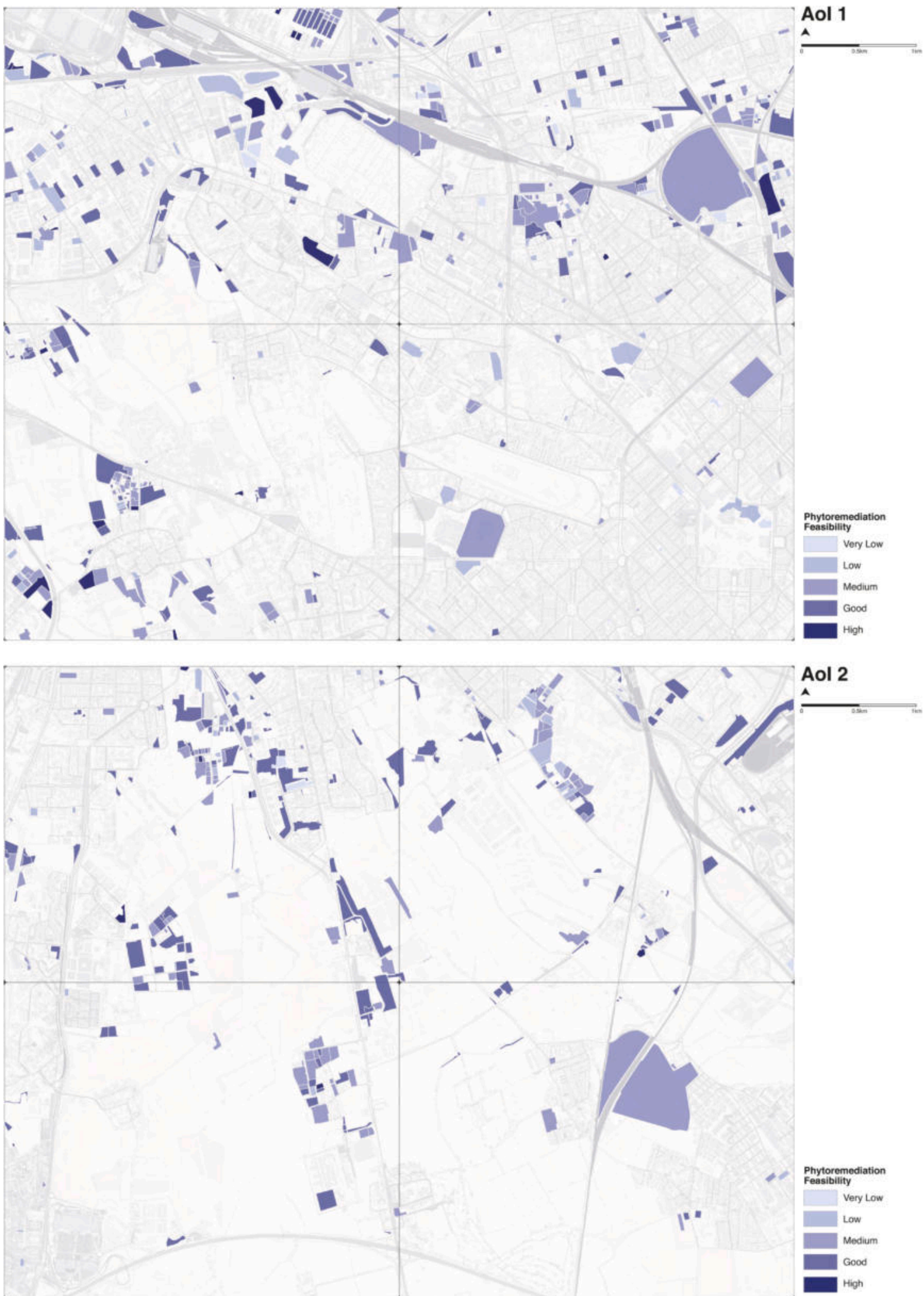


**Fig. 5.** Results of the phytoremediation suitability evaluation for the two areas of interest (AoIs).

ultimately be removed during excavation and building phases. Conversely, sites planned for agricultural or open-space uses—while not identified as formal priorities—remain compatible with phytoremediation, as their non-built condition ensures the long-term persistence of soil and vegetation functions. As shown in Table 6, only four sites in the database overlapped by more than 50 % with green areas designated by the PGT and simultaneously exhibited high suitability for phytoremediation. When also considering good suitability sites, 67 sites demonstrated more than 50 % overlap with public green provision. Overall, however, the majority of mapped sites were not included

**Table 4**
Results of the evaluation, number of sites classified, and total dimensions of the sites.

| Evaluation | Number of sites | Dimensions (ha) |
|---|---|---|
| Very low suitability (< 2) | 36 | 12.96 |
| Low suitability (2–3) | 92 | 56.40 |
| Moderate suitability (3–4) | 261 | 261.69 |
| Good suitability (4–5) | 303 | 197.46 |
| High suitability (5–6) | 28 | 20.73 |
| Total | 720 | 549.24 |

within existing or planned green zones, nor did they exhibit substantial overlap.

Since soil regeneration through phytoremediation shares the same goal of preserving and enhancing biodiversity as the ecological network, areas falling within or near the network were also prioritized. These areas have the potential to act as linear connectors or stepping stones, mitigating habitat fragmentation and strengthening ecological continuity. To evaluate this relationship, a spatial intersection was carried out between the *Ecological Network Nodes* (Database I), their 150 m and 300 m buffer zones, and the sites evaluated for phytoremediation. The analysis revealed that only nine sites—classified as high suitability—fell within the ecological network or its buffer zones. Expanding the scope to include good suitability areas, 136 sites were located within or adjacent to the ecological network. Yet, as in the case of green provision, most of the identified areas lie outside or distant from the main ecological corridors.

The final step involved the intersection with the *Register of Contaminated Sites (AGISCO)* (Database G). For this purpose, attention was focused on standby AGISCO sites—defined as those listed as “to be inquired” for over one year, “potentially contaminated” for more than five years, or “contaminated” for more than ten years without active remediation. To complete the spatial coverage, missing AGISCO geometries of interest were reconstructed and mapped based on known contamination boundaries, as described in Section 2.2 (Open-source data for brownfield identification). These standby AGISCO sites were prioritized because their prolonged inactivity makes them suitable for long-term reclamation processes using nature-based or biotechnological techniques. Among these, 13 out of 33 mapped areas (including eight newly delineated) were associated with an active AGISCO record and fell within the good or high suitability categories for phytoremediation. Of these, five contained information on contaminant types, generally involving a combination of organic (hydrocarbons) and inorganic (metals) pollutants.

### 3.3. Discussion and limits of the study

The research demonstrates that integrating open-source datasets with satellite image interpretation represents an effective strategy for identifying areas in need of soil regeneration (RQ1). The harmonization of multiple datasets with updated satellite observations enabled the creation of a detailed inventory of degraded sites. Results show that approximately 6.8 % of the total surface of the two areas of interest (AoIs) corresponds to sites potentially requiring soil regeneration, highlighting the extent of land degradation within the analysed context. These findings confirm the widespread yet fragmented nature of urban degradation across the Milan Metropolitan Area (MMA)—a pattern typical of post-industrial cities.

Unlike many studies on phytoremediation that focus on site-suitability analyses at a broad territorial scale or on specific industrial compounds (Chatterjee, 2023), this research adopts a fine-grained, spatially explicit approach combining detailed mapping and satellite image interpretation. This micro-scale analysis allows for a more precise understanding of how diverse urban uses and misuses contribute to soil degradation—an aspect often overlooked in broader environmental assessments targeting more homogeneous territories. The micro-scale perspective also offers advantages in terms of scalability and adaptability. Remote sensing techniques and typological classification have already been successfully applied to detect specific forms of degradation, such as illegal dumping (Devesa and Brust, 2021). The typological mapping developed here provides a foundation for future automated systems for site recognition, potentially applicable across broader urban territories. This increases the transferability of the methodology to other metropolitan contexts pursuing similar environmental regeneration strategies. However, given the complexity and gradual nature of degradation processes—occurring across multiple spatial and temporal scales and driven by both anthropogenic and natural factors (Keyserlingk et al., 2023)—the concept of degradation itself remains open to interpretation. This makes it challenging to establish standardized criteria for recognizing and categorizing degradation levels. The typologies identified in this study are therefore specific to the historical and contemporary conditions of Milan, shaped by its industrial legacy, land-use transformations, and patterns of abandonment. As such, they would require recalibration or integration if applied to different settings that do not share similar historical and urban trajectories.

In the broader literature on phytoremediation, most studies tend to analyse plant species’ capacity to remediate specific pollutants

**Table 5**
Good and high suitability sites classified according to the mapped typologies.

| Themes and Sub-categories | | Good suitability | | High suitability | | Totals | |
|---|---|---|---|---|---|---|---|
| | | Number of sites | Dimensions (ha) | Number of sites | Dimensions (ha) | Number of sites | Dimensions (ha) |
| Dismissed | Total | 222 | 175.95 | 28 | 20.73 | 250 | 196.68 |
| | Productive or technological areas | 12 | 10.41 | - | - | 12 | 10.41 |
| | Residential areas or offices | 4 | 4.80 | - | - | 4 | 4.80 |
| | Rural structures | 8 | 3.92 | 1 | 0.26 | 9 | 4.18 |
| | Waste dumping sites and/or informal structures | 13 | 5.90 | - | - | 13 | 5.90 |
| | Barren and/or abandoned spaces | 185 | 150.92 | 27 | 20.47 | 212 | 171.39 |
| Inactivity | Total | 81 | 21.51 | - | - | 81 | 21.51 |
| | Storage of inert or construction materials and/or degradative activities | 1 | 0.11 | - | - | 1 | 0.11 |
| | Informal urban gardens | 80 | 21.40 | - | - | 80 | 21.40 |


**Fig. 6.** Results of the spatial intersection with the urban green provision, ecological network, and AGISCO standby sites.

(Fischerová et al., 2006; Olajiire-Ajayi et al., 2024). While these works are fundamental in demonstrating the biological effectiveness of phytoremediation, they do not provide practical guidance to support local administrations and land managers in selecting this approach over traditional remediation techniques. Addressing this gap, the present study develops a spatial, multi-criteria evaluation framework to determine which degraded sites are most suitable for phytoremediation (RQ2). The model integrates five weighted variables—free soil, vegetation cover, soil texture, soil organic carbon content, and site dimension—each representing a key factor influencing phytoremediation

**Table 6**
Results from the intersections with the prioritization datasets.

| Phytoremediation evaluation | Good suitability | | High suitability | |
|---|---|---|---|---|
| | Number of sites | Dimensions (ha) | Number of sites | Dimensions (ha) |
| Public green provision PGT— overlay ≥50 % | 67 | 43.00 | 4 | 4.41 |
| Public green provision PGT—overlay < 50 % | 236 | 154.46 | 24 | 16.32 |
| Ecological network—within the node | 60 | 34.31 | 3 | 0.86 |
| Ecological network—150 m buffer | 43 | 21.29 | 3 | 1.20 |
| Ecological network—300 m buffer | 33 | 20.61 | 3 | 0.62 |
| Ecological network—no inclusion | 167 | 121.25 | 19 | 18.05 |
| Overlay with AGISCO on standby | 3 | No intersection | 2 | No intersection |
| Overlay with AGISCO on standby remapped areas | 8 | No intersection | 0 | No intersection |

feasibility. Approximately 40 % of the degraded sites within the two AoIs exhibit favourable ecological and spatial conditions, confirming the significant potential for applying this plant-based remediation technique in urban contexts.

Recognizing the limitations of phytoremediation—such as long timeframes, variable efficiency, and delayed land reuse—the study also aimed to identify which sites could be prioritized for its application (RQ3). The analysis indicates that sites with stalled remediation proceedings or those designated for public green uses hold the highest potential, as they align with current urban policies and present greater feasibility for implementation. Likewise, sites located within the ecological network defined by the *Territorial Government Plan (PGT)* could be prioritized, since they may function as ecological connectors or stepping stones within the broader green infrastructure. Among these, areas with ongoing or suspended industrial activities and high real-estate value—where redevelopment pressures are strong—could benefit from an adaptive remediation framework (Palma et al., 2020), combining phytoremediation with traditional techniques to balance environmental restoration with redevelopment objectives. Conversely, abandoned sites with no immediate real-estate interest, particularly those within the ecological network or designated for urban green provision, are ideal candidates for full-site phytoremediation and long-term ecological restoration.

A key limitation of this study is that it does not differentiate between public and private land ownership. The feasibility of implementing phytoremediation on private properties depends on landowners' willingness and capacity to allocate land for the time required for effective remediation. This factor should be considered in future planning and policy frameworks to ensure wider and more equitable implementation. In such cases, adaptive remediation strategies may also prove effective, allowing partial reuse of land while progressively restoring other portions through sustainable, plant-based techniques.

Overall, although this study developed a tool to identify, assess, and prioritize sites suitable for phytoremediation—supporting public authorities in adopting sustainable remediation approaches—it must be acknowledged that the temporal dimension remains the main constraint. Phytoremediation requires long timeframes, which often discourage municipalities and private developers due to delayed returns on investment. Nevertheless, this temporal aspect can also be reframed as an opportunity for temporary and adaptive land uses. During the remediation period, these sites could host experimental plots, biodiversity research, or community gardens, turning latency into an active phase of ecological and social regeneration (Palma et al., 2020; Sleegers, 2010).

## 4. Conclusions

Phytoremediation represents a long-term, nature-based solution that restores degraded soils without generating negative environmental impacts. Beyond its technical function, it enhances the aesthetic quality of remediation processes while delivering multiple ecosystem services (ES) that improve urban liveability. These services are essential for fostering urban resilience and sustainability, aligning with global environmental agendas such as the *EU Nature Restoration Law* and the *Global Biodiversity Framework 2030*.

In complex metropolitan contexts such as the Milan Metropolitan Area (MMA), soil reclamation is increasingly necessary to preserve and enhance soil health. The proposed analysis serves as an effective screening tool to identify and map areas showing signs of potential degradation related to urban uses and misuses, and to recognize those most in need of regeneration strategies. Since the method focuses on soil and spatial conditions indicative of phytoremediation feasibility—rather than direct contamination measurements—it provides a cost-effective and proactive strategy for identifying and prioritizing areas suitable for nature-based remediation. By leveraging openly accessible environmental and planning datasets, the approach accelerates the early phases of environmental assessment and supports evidence-based decision-making for sustainable land management.

The results suggest that numerous urban sites could benefit from sustainable remediation projects. Although these areas differ in ownership status, degrees of soil impairment, and social expectations, they collectively represent valuable opportunities to enhance natural capital, strengthen biodiversity, and improve urban environmental quality for local communities. Moreover, the study highlights that some site typologies are particularly promising for the application of phytoremediation. While the current research does not account for variables such as remediation timeframes, citizen engagement, or future urban planning projections, these aspects should be addressed in subsequent studies and pilot implementations.

Given their widespread occurrence within the Milan Metropolitan Area and the feasibility of achieving positive ecological outcomes, these identified sites could serve as case studies to further develop operational guidelines for phytoremediation. Advancing this methodological framework is fundamental to encourage public administrations to adopt plant-based remediation technologies and to equip them with practical tools to manage the complexity of implementation processes.

In conclusion, despite its long duration and uncertain economic returns, phytoremediation can play a crucial role in the sustainable management of degraded urban land. The analytical framework presented here can be effectively employed as a decision-support toolkit to guide public administrations in integrating phytoremediation within urban regeneration and environmental planning strategies. Finally, the automation and contextual adaptation of this model could enable its application in fragile territories and in countries with limited financial capacity, where traditional remediation techniques remain economically unfeasible. In this way, sustainable soil regeneration and the enhancement of natural capital could become accessible to a broader range of contexts, contributing to global environmental equity.

## CRediT authorship contribution statement

**Maria Chiara Pastore:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Claudia Ida Maria Parenti:** Writing – review & editing,

Writing – original draft, Validation, Supervision, Methodology. **Laura Sibani:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Lucia Ludovici:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Massimo Labra:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Werther Guidi Nissim:** Writing – review & editing, Writing – original draft, Supervision, Methodology.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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