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Urban grounds for sustainable reclamations: the case study of Milan Metropolitan Area

Suoli urbani per le bonifiche sostenibili: il caso di studio di Città metropolitana di Milano

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ABSTRACT AND KEYWORDS

Urban grounds for sustainable reclamations
Urban development and anthropic activity left a contaminated heritage in the urban system, challenging the regeneration of today's leftover polluted areas. These spaces are usually characterized by abandoned and degradation mainly because of the high cost and bureaucratic complexity of their recovery. The research aims to analyze the relationship between soil health and remediation processes in the Milan Metropolitan Area (MMA) since, due to the past industrial activity of the region, it showcases one of the highest numbers of remediation proceedings (both open and closed) in Italy. In particular, the focus is discussing which areas are most feasible for applying phytoremediation techniques, a sustainable remediation approach that could grant, in addition to soil decontamination, the enhancement of urban ecosystems, providing new green spaces and ecosystem services (ES), promoting new good practices of regeneration and restoration.

Keywords: urban leftovers, brownfields, sustainable remediations, phytoremediation, soil regeneration

Suoli urbani per le bonifiche sostenibili
Lo sviluppo urbanistico e le attività antropiche hanno lasciato un'eredità di contaminazione all'interno del tessuto urbano, ponendo sfide significative alla rigenerazione delle aree inquinate rimaste. Questi spazi sono spesso caratterizzati da abbandono e degrado, principalmente a causa degli elevati costi e della complessità burocratica associati al loro recupero. La presente ricerca si propone di analizzare la relazione tra la salute del suolo e i processi di bonifica nella Città metropolitana di Milano (CMM) che, a causa della passata attività industriale, presenta uno dei più alti numeri di procedimenti di bonifica (sia aperti che chiusi) in Italia. In particolare, l'obiettivo è quello di individuare le aree più idonee all'applicazione di tecniche di fitorimedio, un approccio di bonifica sostenibile che potrebbe garantire, oltre alla decontaminazione del suolo, la valorizzazione e il miglioramento degli ecosistemi urbani, fornendo nuovi spazi verdi e servizi ecosistemici (ES) al sistema città, promuovendo nuove buone pratiche di rigenerazione e recupero di questi spazi.

Parole chiave: residui urbani, brownfields, bonifiche sostenibili, fitorimedio, rigenerazione del suolo

1. Introduction

Soil is a complex system and a vital resource for human life and ecosystem health. It supports biodiversity, plays a key role in water filtration and carbon sequestration, and provides fundamental ecosystem services (ES) necessary for sustaining life on Earth. Given that soil formation occurs at a much slower rate than human timescales, it is regarded as a non-renewable resource (Clunes et al., 2022). Therefore, in the context of global climate change, careful management and preservation of soil are crucial.

In response to these challenges, the concepts of “soil quality” and “soil health” have emerged. Soil quality refers to the ecosystem services that soil provides to humans, primarily in relation to agriculture. Soil health, however, relates to the broader concept of “One Health,” which highlights the interconnectedness of soil with broader sustainability goals and its influence on the health of humans, animals, and the environment (Lehmann et al., 2020).

Currently, soil health – upon which soil functions critically depend – is under threat from various factors, including erosion, compaction, loss of organic matter, and contamination. Human activities, particularly industrial operations, unsustainable land use practices, and urban expansion that results in soil sealing and pollution, are the leading drivers of soil degradation. Consequently, there is an urgent need to quantify and assess the extent of soil degradation to guide strategies for achieving a sustainable future.

According to the 2023 *Rapporto Suolo*, approximately 47% of soils in Italy are classified as being in poor condition, primarily due to erosion, loss of organic carbon, soil compaction, and contamination. Soil contamination, in particular, represents one of the most alarming forms of degradation, especially in urban and industrial areas across Europe. In European cities, urban soils are particularly vulnerable to contamination from various sources, including industrial waste, vehicle emissions, and construction activities. The accumulation of heavy metals and organic pollutants often renders urban soils unsuitable for human use, agriculture, recreation, or construction, posing significant health risks to the population.

Increasing awareness of these dynamics and the global relevance of soil health has led to the adoption of policies and strategies at the European and international levels aimed at soil conservation and protection. In 2021, the European Union adopted the Resolution on Soil Protection and the Soil Strategy for 2030, which seeks to ensure sustainable soil management to preserve ecological functions and underscores the urgency of restoring degraded and abandoned compromised sites.

The traditional way of reclaiming contaminated soil, however, while necessary, is associated with high operational costs and significant environmental impacts. As a result, many brownfield sites remain abandoned, without the possibility of reintegration. Nature-Based Solutions (NBS), defined as actions that are “inspired by, supported by, or copied from nature” (van den Bosch & Ode Sang, 2017), offer promising alternatives. These include sustainable remediation practices such as phytoremediation, which have the potential to remediate polluted lands while simultaneously providing multiple social and environmental benefits (Song et al., 2019).

The aim of this paper is to stimulate reflection on the role that degraded urban areas can play in enhancing the natural capital of cities through the application of sustainable remediation techniques. Despite demonstrating positive results in experimental and laboratory settings, these techniques, particularly phytoremediation, face significant challenges that hinder their widespread implementation. These challenges include the lack of effective strategies for selecting appropriate sites and the absence of a clear evaluation of their benefits compared to traditional remediation methods.

To address this issue, we developed a flexible framework for identifying suitable sites for phytoremediation interventions, taking into account ecological, urban planning, and management factors. This model was designed specifically for the Milan Metropolitan Area (MMA), one of the most polluted regions in Italy and a focal point for numerous reclamation efforts (ISPRA, 2023). Additionally, our goal was to highlight the valuable aspects of the phytoremediation process, which holds the potential to restore urban spaces and provide ecosystem services that align with the city's broader sustainable development objectives.

2. Milan, the post-Fordist city.

The Milan Metropolitan Area (MMA) is characterized by continuous transformation, reflecting its evolving economy. The region's history has been shaped primarily by industrial activity, which began in the late 19th century with the establishment of large mechanical factories on its northern outskirts, such as the renowned Pirelli factories and the "industrial village" of Sesto San Giovanni (Borruso, 1996; Bigatti, 2020). During the 20th century, manufacturing activities spread throughout the region, making Milan one of Italy's most important economic centers. However, by the century's end, socioeconomic shifts, including deindustrialization and demilitarization, prompted a gradual transition in many cities, transforming them into what is now referred to as post-Fordist cities (Ferraresi, 2007). The relocation of industrial activities and the rise of a new economy based on the service sector radically altered the city and its population (Lever, 2001). In this context, the proliferation of abandoned sites, referred to as "voids," "leftovers," and "wastelands," posed the challenge of their reuse and regeneration.

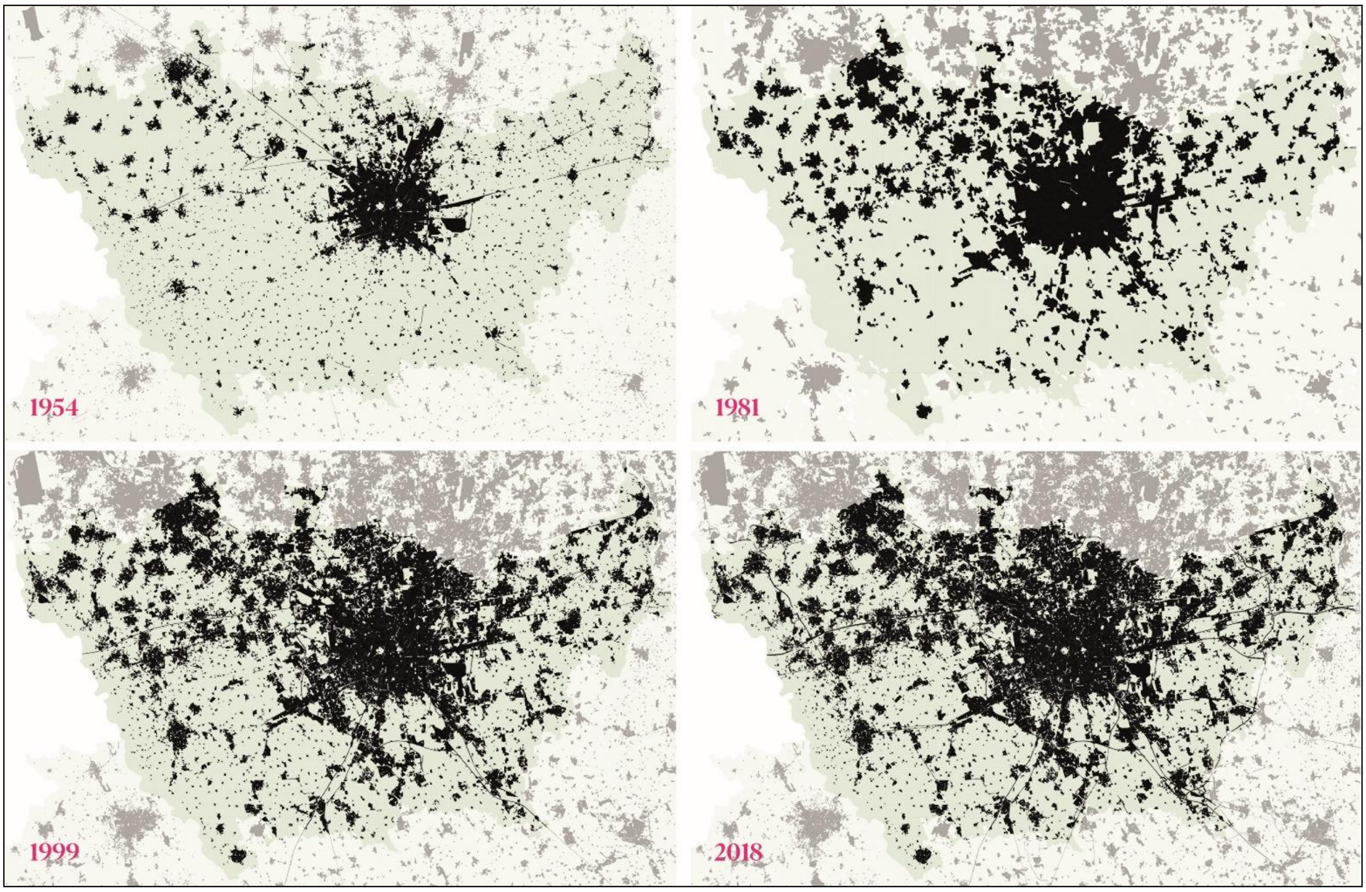
In Milan, the abandonment of former industrial and logistic sites, combined with economic restructuring, led to the transformation of entire neighborhoods, as exemplified by the Bicocca district project (Bolocan Goldstein, 2007). The Expo 2015 mega-event further cemented Milan's reputation as Italy's most "European" city, catalyzing the transformation of urban voids into financial and economic hubs, while attracting global investments and fostering further urban development (Bolocan Goldstein, 2008). The city's rapid expansion, depicted in Figure 1, underscores this trend.

Today, the Milanese region is one of the most urbanized in Italy, with 40.5% of its land classified as urbanized (Forestami, 2019). The northern part is densely built-up, while the southern area, owing to the presence of a regional park and protected area, "Parco Agricolo Sud," retains substantial agricultural land.

In this already densely urbanized environment, the reuse of former industrial sites and other so-called "degraded" areas has become a key priority in the urban agenda, offering opportunities for real estate investors. However, the reclamation of these vacant spaces presents significant challenges, often requiring substantial investments. Many of these sites, neglected for years, are in compromised conditions due to previous industrial activities that may have caused severe soil degradation and contamination, necessitating remediation before reuse.

Several notable transformations have already taken place, including the redevelopment of the Bicocca area on the former Pirelli site, as well as the renewal of Tre Torri and Porta Nuova, both of which were spurred by Expo 2015. However, some large urban voids, often designated as Sites of National or Regional Interest for Reclamation (SIN and SIR), continue to face significant remediation challenges due to the complexity, scale, and severity of contamination. A prominent example is the former Falck Area, whose reuse has been a subject of public debate for decades. An interesting exception is the experimental project on the former Italgas site, where innovative technologies are being tested to preserve a spontaneous forest that has grown on contaminated land, in collaboration with citizens, researchers, and institutions.

Figure 1. MMA expansion from 1954 to 2018

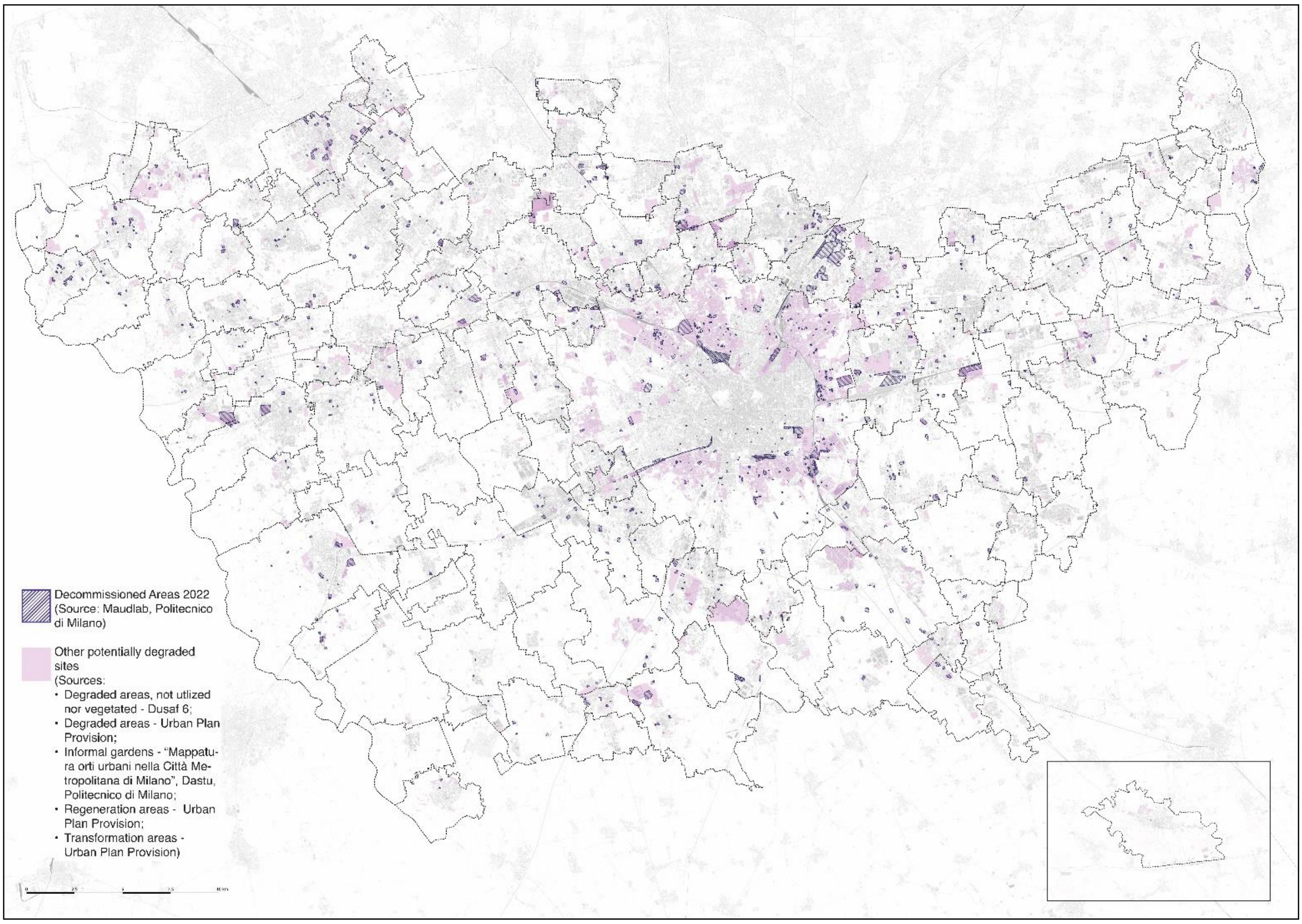


Source: Processing by Lucia Ludovici. Data: DUSAF

Beyond the larger industrial compounds, the Milanese landscape of urban leftovers consists mostly of smaller, widely dispersed elements, similar to the typology of industrial "sheds" (Setti, 1986; Rocca et al., 2022). These spaces are often architecturally undistinguished, degraded, and sometimes occupied by activities such as scrapyards, which further diminish their quality. In addition to these, many "residual" areas can be found in the peri-urban zone. Figure 2 illustrates available mapping data, providing a partial geography of these leftover spaces.
These sites often face potential soil contamination, necessitating remediation interventions. Their reintegration into the urban fabric is complicated by their limited appeal to investors, as the high costs of remediation frequently outweigh the benefits. In such spaces, sustainable remediation techniques, such as phytoremediation, could offer a valuable opportunity for reclamations, contributing to the revitalization of degraded urban zones while increasing green space in the city and providing ecosystem services for the broader public benefit.
Notably, in recent years, the MMA has promoted an ambitious project to integrate urban forestry into urban planning, aiming to increase the city's tree canopy cover and address challenges posed by climate change. This initiative highlights the

potential for exploring phytoremediation as a tool to regenerate these leftover areas, transforming them into green spaces and urban forests that provide significant benefits to both humans and the environment.

Figure 2. MMA dismissed sites and other potentially compromised areas from urban plans



Source: Processing by Laura Sibani

3. The reclamation of contaminated sites in Italy

The remediation of contaminated sites plays a strategic role in local land use planning by enabling the recovery of areas that are compromised and potentially hazardous to human health, thus providing an opportunity for environmental redevelopment. Despite its critical importance to both soil and human health, the technical and regulatory complexity of remediation procedures—due in part to the inherent challenges of managing contamination and in part to the bureaucratic and regulatory framework that has evolved over time—makes the process slow, intricate, and uncertain in its outcomes.

Remediation is one of the most complex activities in environmental protection, not only from a technical and implementation standpoint but, more critically, from a legal perspective. It requires the application of a regulatory framework that governs a range of activities and operations, often leading to unpredictable results.

In Italy, according to ISPRA's latest report, *The State of the Remediation of Contaminated Sites in Italy: Second Report on Regional Data* (2023), based on data updated to 2020, approximately 35,000 sites are undergoing remediation proceedings, with 46% of these cases still ongoing and the remainder completed. Of these, 10,870 sites are located in Lombardy, the region with the highest total number of remediation sites in Italy (ISPRA, 2023).

3.1 Milan Metropolitan Area (MMA) and Milan Municipality situation - AGISCO database

Within the regional context, MMA has the highest number of both open and concluded reclamation proceedings. This is largely driven by the city's active real estate market, which has spurred extensive transformation and redevelopment processes involving both buildings and industrial heritage.

These processes often require, as a matter of regulation (Hygiene Regulation), preliminary investigations to ensure that contamination thresholds (CSC), defined in Annex V of Part IV of Legislative Decree No. 152/2006, have not been exceeded. These thresholds vary based on the intended land use (e.g., Class A: public and private green spaces and residential areas; Class B: commercial and industrial use). Additionally, the MMA, with its extensive industrial past, has inherited numerous brownfield and contaminated sites. The regulatory complexity and high remediation costs, coupled with the difficulty of attracting investment, often lead to prolonged inactivity, leaving these areas outside the urban system for extended periods.

Since 2013, the Lombardy Regional Agency for Environmental Protection (ARPA) has managed the *Anagrafe e Gestione Integrata dei Siti Contaminati* (AGISCO) database, a registry of all remediation proceedings in the region, born from the union of two pre-existing databases. According to ARPA Lombardia data extracted from the AGISCO database in April 2023[1], 5,606 sites in the MMA have been subject to proceedings. Of these, 2,553 were preliminary investigations, while 3,053 involved a remediation proceeding.

Among the 2,553 areas in the preliminary phase, about 82% were found to be uncontaminated after the initial investigation. This highlights the extent of real estate and urban transformation in the metropolitan city, which necessitates frequent screening analyses for any change in land use.

Regarding the 3,053 remediation processes, 527 were identified as contaminated, 415 were potentially contaminated, and 1,716 sites had completed remediation.

Considering the totality of the 5606 proceedings in MMA and 2023 as the year of the last data update, several observations can be made regarding their duration. However, it is important to note the difficulty in systematizing information from the AGISCO database due to inconsistencies in data entry and occasional editorial errors. Approximately 45% of the closed proceedings—classified as "uncontaminated," "uncontaminated following Risk Analysis," or "remediated"—were concluded within one year, with an average closure time of approximately 3.4 years. In contrast, about 33% of ongoing proceedings have been open for 11 to 20 years, with an average duration of around nine years.

When examining the duration of proceedings based on contamination status, 69% of uncontaminated cases are closed within one year. However, for cases categorized as "to be inquired," 30% have been ongoing for 2 to 5 years, and 26% for 11 to 20 years. The prolonged preliminary investigation phase, despite being the initial step of the remediation process and expected to be relatively swift, could be delayed due to various factors, such as:

- Difficulty in identifying the party responsible for the contamination;
- Inaction by the municipality or a lack of funding or interest in conducting the investigation (particularly if the responsible party is unidentified or insolvent);

- Challenges in finding qualified firms to perform sampling or delays in laboratory analyses;
- Ongoing legal disputes.

For potentially contaminated sites that exceeded contamination thresholds (CSC) after initial investigations, 43% have been in progress for 1 to 5 years, while 34% have been open for 11 to 20 years. These sites, stalled for long periods, pose a significant management issue, as they remain unusable due to potential health risks and are left without remediation aside from initial emergency safety measures (MISE).

For sites confirmed as contaminated after a risk analysis, 30% have been in progress for 11 to 20 years, 28% for 2 to 5 years, and 13% for over 20 years. The extended duration of these proceedings likely reflects the longer timeframe required for both prior phases and the actual remediation, which can take years depending on site's complexity.

Conversely, 48% of remediated cases were closed within 2 to 5 years, 18% in under a year, and about 11% took more than 10 years to conclude. These figures suggest that the severity and extent of contamination are factors in determining the length of the remediation process. Shorter remediation times may indicate smaller site size or less extensive contamination, even in cases of severe pollution.

Finally, it is noteworthy that about 2,699 proceedings, approximately 48% of the MMA total, are within the Municipality of Milan, with 1,590 classified as reclamation proceedings and 1,190 as preliminary investigations. Of these 2,699 proceedings, about 75% have been concluded. This underscores Milan's role as a "driving force" in remediation efforts, not only accounting for the highest number of proceedings—due in part to the increasing spread of urban transformation and regeneration—but also demonstrating significant efficiency in concluding preliminary investigations and reclamation operations.

4. Sustainable remediation and Phytoremediation

The remediation of contaminated land can be achieved through various techniques, broadly categorized into two main approaches: "In Situ" and "Ex Situ" interventions. In Situ methods treat contamination directly at the site without removing the soil, allowing for the remediation of pollutants in their original location. Conversely, Ex Situ techniques involve excavating the contaminated soil, which may then be treated either on-site or transported to off-site facilities for treatment or disposal at licensed landfills.

Historically, the management of contaminated sites has prioritized the mitigation of risks to human health, to ensure the rapid return to use of the area (Bardos, 2014). Consequently, remediation strategies that enabled the swiftest return to site functionality were often prioritized.

Nowadays, however, the extent of soil pollution issues and the corresponding actions to address them spark a significant discussion about attaining sustainability in the remediation processes. It is recognized that the focus should not only be on removing contamination threats but also on the methodologies employed to achieve remediation.

"Sustainable remediation," defined as an approach that seeks to balance environmental, social, and economic considerations (NICOLE, 2011), offers promising responses to the complex environmental challenges related to soil and water contamination. This approach integrates innovative technologies and natural processes to minimize the ecological, social, and economic impacts of remediation.

Among these technologies, phytoremediation stands out due to its use of plants and microorganisms that can absorb, degrade, or stabilize soil contaminants. This technique has a low environmental impact, as it leverages natural biological processes to decontaminate soils.

Vegetal species can perform soil reclamation actions through different strategies, the main ones including phytodegradation, phytoextraction, phytostabilization, phytovolatilization, and phytometabolism. These strategies involve processes such as the uptake of pollutants and their degradation into smaller, non-toxic components that plants utilize for growth; the extraction and accumulation of contaminants in the plants' shoots and leaves; the immobilization of contaminants to prevent their migration off-site; the transpiration of these substances into the atmosphere as gases; and the assimilation of organic contaminants (primarily nutrients) that are incorporated into the plant biomass and used for plants' growth, (Kennen and Kirkwood, 2015).

However, given that all these actions are natural ones, phytoremediation, as visible in Figure 3, is often associated with longer remediation timelines, delaying immediate site reuse. Furthermore, its effectiveness is limited by the type of contaminants involved, and uncertainties remain regarding its success due to varying environmental and climatic factors. These challenges underscore the need for careful planning, management, and maintenance throughout the phytoremediation process.

For these reasons, despite the evidence of phytoremediation's efficiency in laboratory settings and its potential to deliver multiple co-benefits, its practical application remains limited (Guidi Nissim et al., 2023; Podhajska et al., 2023). The slower remediation rates and site-specific constraints have hindered its widespread adoption.

Figure 3. Traditional remediation vs Phytoremediation

Traditional remediation techniques:	Phytoremediation mechanisms:
PROs:	**PROs:**
• Timeframe allowing a return to use in a short period; • Certainty of results	• Low environmental impact; • Contained cost compared to traditional techniques • Form of ri-naturalization of the sites; • Ecosystem services carried out by plants
CONs:	**CONs:**
• HIgh environmental impacts; • High costs	• Timeframe not allowing a return to use in a short period; • Uncertainty (depending on the type of pollutants to be reduces) • Project maintenance

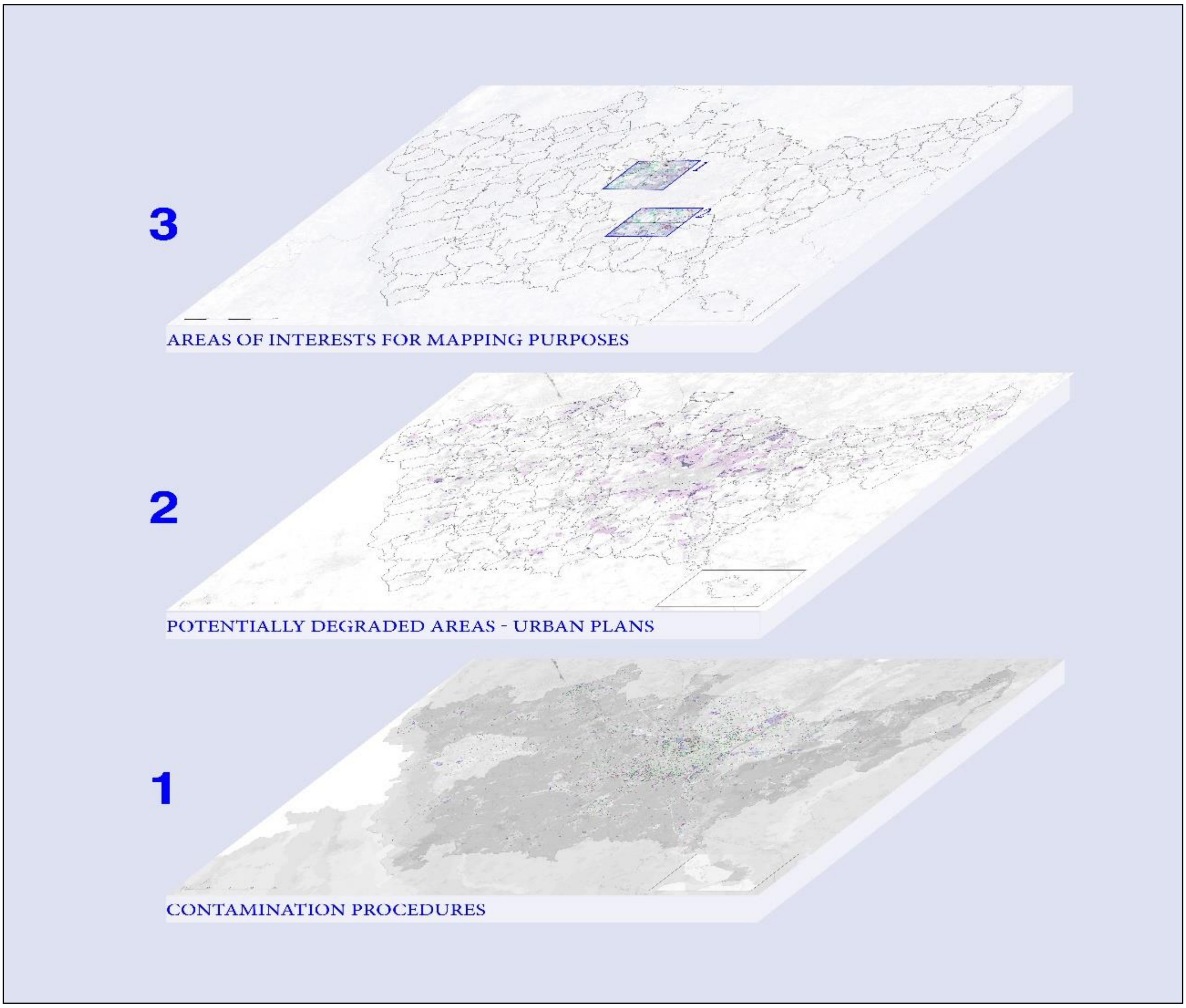
Source: Processing by Laura Sibani

Given these considerations, the present research, conducted in collaboration with biologists and agronomists from the University of Milano-Bicocca, aims to identify areas with potential soil degradation due to anthropogenic activities, stratified over time and to select the most promising sites for phytoremediation interventions.

5. Mapping the areas of soil regeneration

For the purpose of mapping the areas needing soil regeneration, we implemented a quali-quantitative methodology, analyzing and harmonizing several existing open-source databases containing information on land use, degradation, decommissioning, soil characteristics, and urban greenery. We focused on two specific sectors (as depicted in Figure 4), on the northwest and southern borders of the Milan municipality.

Figure 4. The overall process and the two sectors of interest in the MMA



Source: Processing by Laura Sibani

The two areas are both about 40 square kilometers in size so as to be comparable and to represent a significant number of cases while at the same time having a small size to ensure accuracy in the mapping process. The locations chosen represent two different situations on the borders of the municipality of Milan: the northern area has a greater number of industrial and productive sites and a large number of areas undergoing transformation. The area to the south, on the other hand, which is part of the Parco Agricolo Sud, has many agricultural sites, informal urban orchards, and areas degraded by anthropic activities.

Rather than merely relying on the existing dataset, we constructed new data through qualitative interpretation of satellite images. These satellite images were used both to ensure the accuracy of the existing datasets and to identify patterns and features

indicating the different categories of our interest for mapping purposes.
The new database differentiated between two main categories: decommissioned areas and “active” areas, with a focus on both proper and improper land uses that may contribute to soil degradation. Table 1 outlines the different typologies identified and categorized within these groups.
The mapping outcome provides a “snapshot” of all areas with potential for soil regeneration, where current or past anthropogenic activities may have compromised land quality.

Table 1. Main themes and typologies individuated

Dismissed	In activity
Productive or technological areas	Storage of inert/building materials and/or degradational activities
Residential areas or offices	Informal urban gardens
Rural structures	Construction sites
Barren and/or abandoned spaces	
Waste dumping sites and/or eventual informal structures	

Source: Processing by the research team

After identifying potentially degraded areas, we enhanced the database by analyzing satellite images to assess the degree of free soil and vegetation cover. We also incorporated data on soil obtained from the open-source Lombardy’s Soil Database. Following this, we assigned weight to various categories of interest, allowing us to evaluate the suitability of each area for phytoremediation.
This evaluation was further refined by prioritizing sites with ongoing legal or stalled remediation proceedings, those designated for public green space, or those located near ecological networks. The results of this evaluation are currently under publication.
From this assessment of the area's suitability for phytoremediation, the research aims to develop applicative guidelines that provide insight into the phytoremediation techniques to be implemented depending on the specific soil and area characteristics such as pH, texture and vegetation cover.

6. Conclusions

Soil health has emerged as a critical focus in the governance and politics of urbanized territories, as the legacy of brownfields and severely degraded sites—resulting from both historical and contemporary human activities—poses significant risks to human health and the environment (Van Liedekerke et al., 2014). Concurrently, there is a growing imperative to protect pristine soils, often referred to as “greenfields,” from development pressures. This underscores the critical need to reclaim, reintegrate, and re-signify abandoned or contaminated spaces within urban environments. Achieving this objective, however, requires comprehensive planning and strategic interventions aimed at addressing soil degradation and fostering sustainable land use practices.
Despite the myriad challenges associated with soil contamination, prolonged

neglect, and improper land use, these "leftover" areas hold considerable potential as valuable resources for enhancing urban systems when subjected to sustainable remediation practices. The implementation of phytoremediation strategies not only facilitates the decontamination of these sites but also contributes to broader urban well-being objectives. As a nature-based solution (NBS), phytoremediation involves the plantation of vegetation species capable of degrading pollutants, thereby augmenting the city's natural capital and green spaces while providing essential ecosystem services to mitigate the impacts of climate change in urban environments (Cundy et al., 2016).

This research underlines that the potential to improve urban soil qualities is especially evident for certain kinds of spaces, both dismissed or in activity.

Uncultivated or barren plots and informal urban gardens have emerged as the typologies most suitable for phytoremediation. Additionally, certain industrial brownfields and areas classified as illegal dumps could also be effectively treated using phytoremediation, provided that the extent and severity of contamination, along with minimal demolition or soil decompaction operations, render such efforts feasible.

While the study highlights the potential for large scale implementation of phytoremediation, challenges such as the long timeframe required for decontamination pose limitations, especially for private landowners seeking quicker returns on investment.

Therefore, public areas, especially those within the ecological network or belonging to the urban plan's green provision, are ideal candidates for this approach, as they can be preserved as green spaces post-reclamation, contributing to the long-term sustainability and resilience of urban environments.

In light of this, the proposed methodology serves as a robust framework for identifying suitable sites for phytoremediation, emphasizing their potential as catalysts for urban regeneration. This approach equips decision-makers with the tools to pinpoint key sites for sustainable reclamation initiatives and implement remediation projects that can transform degraded and neglected areas into public parks for community benefit. Moreover, the methodology's adaptability across various urban contexts makes it a valuable resource for promoting the diffusion and application of phytoremediation practices.

Therefore, it is advisable to develop comprehensive guidelines outlining potential strategies, timelines, and cost estimates for implementing effective remediation interventions in the areas identified as most feasible for phytoremediation.

Such guidelines would provide essential support and practical information to the entities responsible for executing these interventions, thereby incentivizing the broader adoption of this innovative approach.

Notes

1. The following data are reprocessed by the research team from data in shape and Excel table format provided by ARPA Lombardy following a request for access to the records in April 2023.

Author Contributions

Collaboration Group Member M.C.P., C.P., L.L., L.S., W.G.N., M.L.; Conceptualization M.C.P., C.P., L.L., L.S.; Methodology C.P., L.L., L.S.; Software L.S.; Writing - Original draft preparation C.P., L.L., L.S.; Writing - Review & Editing M.C.P., L.L., L.S.; Visualization L.L, L.S.; Supervision M.C.P., M.L., C.P., W.G..N; Project Administration M.C.P., M.L.; Funding Acquisition M.C.P., M.L.

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Conflicts of Interest
The authors declare no conflict of interest.

Originality
The authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere, in English or any other language. The manuscript has been read and approved by all named authors and there are no other persons who satisfied the criteria for authorship but are not listed. The authors also declare to have obtained the permission to reproduce in this manuscript any text, illustrations, charts, tables, photographs, or other material from previously published sources (journals, books, websites, etc).

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