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Interdisciplinary Approach to Regenerate Contaminated Urban Sites with Novel Ecosystems: The Multi-Layer Analysis of La Goccia Forest, a Case Study in Milan

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Abstract

In the face of mounting challenges related to limited availability of urban land and ecological degradation, emerging novel ecosystems offer unique opportunities for ecological regeneration, social redefinition of space, and alternative urban visions. This study presents the multi-layer analysis of the Goccia Forest in Milan (Italy), a wild urban woodland that has developed over sealed and polluted post-industrial land, aiming to investigate the potential of this novel ecosystem to sustain Nature-based Solutions (NbSs). Using an integrated approach (surveys on fauna, vascular flora, lichens, analysis of forest evolution, mapping of sealed surfaces, and soil characterization) the research looks at the novel ecosystem as a whole, highlighting its ecological dynamics and Ecosystem Services (ES). La Goccia Forest serves as a prime example of how the implementation of NbSs is intricately intertwined with the spontaneous regeneration of urban brownfields. The present study offers the opportunity to rethink urban policies, ensuring their alignment with the demands of the population and the latest scientific knowledge.

Keywords: brownfields; informal greenspaces; Nature-based Solutions; post-industrial landscape; soil desealing; spontaneous vegetation; urban regeneration; urban woodlands

1. Introduction

1.1. Wild Urban Woodlands as Novel Ecosystems

In both expanding and shrinking cities, abandoned urban land has become a critical setting for the emergence of spontaneous vegetation [1] and the development of urban wild spaces [2,3]. As posited by Kowarik and Körner [4], wild urban woodlands can be defined as a particular component of the urban forest matrix comprising stands of woody plants within the impact area of cities, in which a large leeway for natural processes makes possible a convergence toward wilderness [4]. These spaces, which range from extensive post-industrial landscapes to small, fragmented patches between infrastructure systems [5], often arise in neglected areas such as railway corridors, road verges, or former industrial sites [6,7]. Their formation is typically linked to the abandonment of previous land uses and the delay or suspension of new developments due to economic or administrative constraints [8,9].

These so-called "informal greenspaces" [6] are often outside formal planning processes, lacking legal status, regular maintenance, or recognition as valuable urban green areas. However, their liminal and unmanaged nature frequently allows for the emergence of spontaneous vegetation through natural succession [10]. Over time, these processes can result in the formation of spontaneous urban woodlands or secondary landscapes [11,12], where first-growth trees establish themselves on anthropogenic substrates and uneven, disturbed soils.

From an ecological standpoint, these urban woodlands can be understood as novel ecosystems [13]. The plant species that colonize these environments tend to be resilient, including non-native and sometimes invasive species that are well-adapted to the site's chemical and physical stressors [14,15]. Nevertheless, some of these species have been shown to improve soil quality and create ecological niches that can support native flora and fauna [16], including diverse insect, bird, and mammal species. As a result, spontaneous woodlands can promote both alpha-diversity at the site level and beta-diversity across the broader urban landscape, helping to counteract biotic homogenization [17].

1.2. Ecosystem Services of Wild Urban Woodlands

As stated, wild urban woodlands often remain "invisible" from a social and an administrative perspective [18]. Indeed, especially in Mediterranean cities, the Ecosystem Services (ES) that this kind of nature provide [19–22] are often neglected. In many cases, they are viewed not as ecological communal land by public authorities, but as underutilized spaces awaiting redevelopment and capitalization [18].

To identify, quantify, and preserve the ES (i.e., provisioning, regulating, cultural, and supporting services) provided by wild urban woodlands is therefore critical not only to understand their role within the social and ecological context of cities but also to make them visible to public administrations and stakeholders (Millennium Ecosystem Assessment, 2005; TEEB, 2010).

Wild urban woodlands can offer a wide array of ES, such as carbon sequestration, soil remediation and climate mitigation [23,24]. Moreover, such woodlands can support animal and plant biodiversity [25]. Eventually, these spaces can be pivotal to produce forms of collective memory and alternative urban imaginaries [8,26] and can enhance mental health and well-being of citizens [27]. Indeed, wild urban woodlands can help connecting people with nature [2,3,28] and the role of citizens is pivotal for its conservation and enhancement [29,30].

1.3. Soil Remediation in Wild Urban Woodlands

In the last decade, with the widespread recognition of the ES associated with green areas, phyto- and bioremediation are increasingly being proposed as Nature-Based Solutions (from here on, NbSs) for contaminated land remediation and brownfield redevelopment in cities [31,32] such as for wild urban woodlands in contaminated lands. These approaches offer alternatives to traditional remediation techniques, which are typically resource-intensive, socially disruptive, and ecologically reductive. Conventional chemical and physical remediation methods not only entail significant financial and energy costs but also often degrade the ecological functions of the soil.

In contrast, phytoremediation techniques aim not only to mitigate contamination but also to harness the co-benefits of urban woodlands enhancing social inclusion, biodiversity, and community well-being [31]. Studies such as Prach et al. [33] show that passive restoration based on spontaneous succession may outperform technical restoration in terms of biodiversity outcomes and invasive species control.

This paradigm shifts from purely technical decontamination to ecologically integrated land rehabilitation and requires a comprehensive understanding of the established ecosystem. In this context, spontaneous vegetation becomes a central actor. Naturally selected plant species are already adapted to the local contamination profile, often reducing the need for active soil amendments and long-term maintenance interventions [31]. Across Europe, various projects—such as Buiksloterham in Amsterdam or Landschaftspark Duisburg-Nord in Germany—have illustrated how former industrial sites can be transformed into ecologically functional and socially inclusive spaces [34–37]. Yet few of these cases have fully integrated spontaneous vegetation, local microbial communities, and long-term ecosystem service monitoring into a unified restoration framework. This gap underscores the need for interdisciplinary, multi-layered models that recognize the regenerative potential of novel ecosystems from both ecological and socio-political perspectives.

1.4. Goals of Study

The Goccia Forest, a novel ecosystem that has developed over partially sealed and contaminated soils of a post-industrial area in Milan (Italy), is examined as a case study to explore how spontaneous vegetation, soil conditions, and flora and fauna diversity interact within a complex and evolving urban woodland.

The study of the Goccia Forest is relevant for several reasons: its relatively high extension and density of vegetation, despite being located on largely sealed and disturbed land; the conflictual social processes that have seen it involved over the years; the fact that it is almost completely enclosed by railway tracks, making it partially isolated from the surrounding urban area.

The specific goals of the study are as follows:

- To present an interdisciplinary, multi-layered approach to comprehend the ecological dynamics of wild urban woodlands using the Goccia Forest as a case study;
- To identify Ecosystem Services currently provided by the wild urban woodland Goccia Forest, or those services that could be enhanced in the future through NbSs.

2. Materials and Methods

2.1. Overview of the Study Site

2.1.1. The Gas Works of Bovisa and the 'Goccia Forest'

The metropolitan area of Milano has the highest percentage of soil consumption in Italy [38]. Because of its industrial past, the area undergoes a massive decommissioning phenomenon related to contamination. According to data from the Regional Environmental Agency (Agenzia Regionale per la Protezione Ambientale, ARPA), 5000 sites are undergoing a remediation process in the Lombardy region. Almost 500 sites (i.e., more than 750 hectares) are officially categorized as "contaminated". Due to the relevance of the urban land use dynamics, encompassing both expansion and abandonment, this region is an interesting case study for investigating the presence of informal biodiversity in an urban context [39]. A good example of a contaminated industrial area where a dense and extensive novel ecosystem has been spontaneously developed is the so-called 'Goccia Forest' (Figure 1). The site is located on the northwest axis of the city, along which important projects such as Porta Nuova, Scalo Farini, and MIND arise.

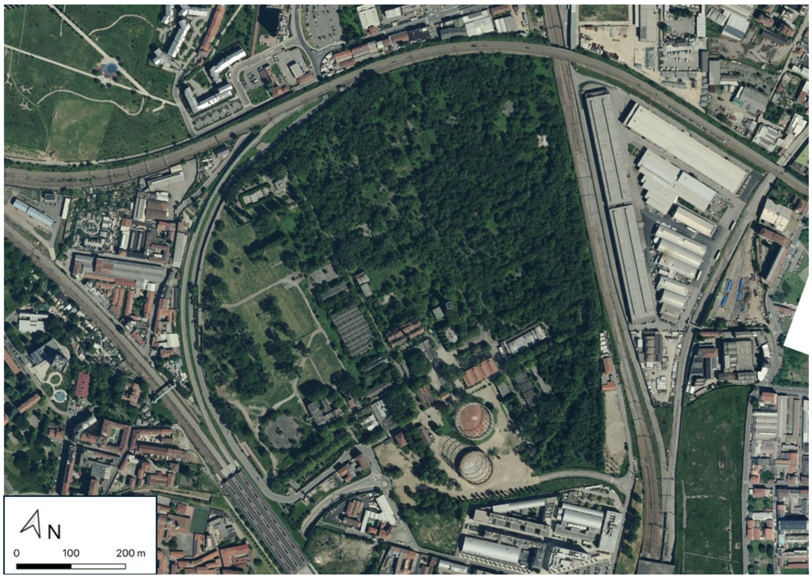

Figure 1. Ortofoto of the Goccia Forest from Google Hearth, 2021.

The 'Grandi Officine del Gas della Bovisa' Gas Works was the largest energy production plant in Milan and one of the most active in Europe. It was established in 1905 on the north-western edge of the city, in an area already occupied as a railway interchange. Besides the Grandi Officine del Gas della Bovisa, within the drop formed by the tracks (approx. 64 ha), numerous factories, workshops, and warehouses were installed during those years, defining this area as an important industrial hub for the city.

Within the Grandi Officine del Gas della Bovisa, gas was produced from the gasification of coal through the process of cracking. Gas was stored in gasometers, from which it was then distributed to the city. These industrial processes and subsequent plant demolitions have produced waste, left disturbed, largely sealed, and heavily contaminated soil.

Trains arrived at the site, to release the coal that would be processed via tracks that entered directly into the Gas Works, as can be seen in Figure 2.

The workshops were gradually abandoned, from the first demolitions in the late 1960s until the final decommissioning, after a tree planting initiative undertaken by the last owner, Azienda Energetica Municipale (AEM), in 1994. In the same year, the site was included in the list of the national Sites of Interest (Siti di Interesse Nazionale—SIN) for the high pollution detected in the soil and in the subsoil. In 2013, the site was downgraded to a Site of Regional Interest (Sito di Interesse Regionale—SIR) and then came under municipal jurisdiction following the conferral by the Lombardy Region.

During the subsequent years of abandonment, particularly between 2003 and 2015, a heterogeneous novel ecosystem developed, starting from several stands of trees already present during the industrial activity and from the planting that took place in recent years of land use. The 'Goccia Forest' is a diverse ecosystem comprising thousands of trees, grown on a technosol composed of relics of forest soil, disturbed soil with asphalt sealing, industrial waste, and surfaces of concrete sealings.

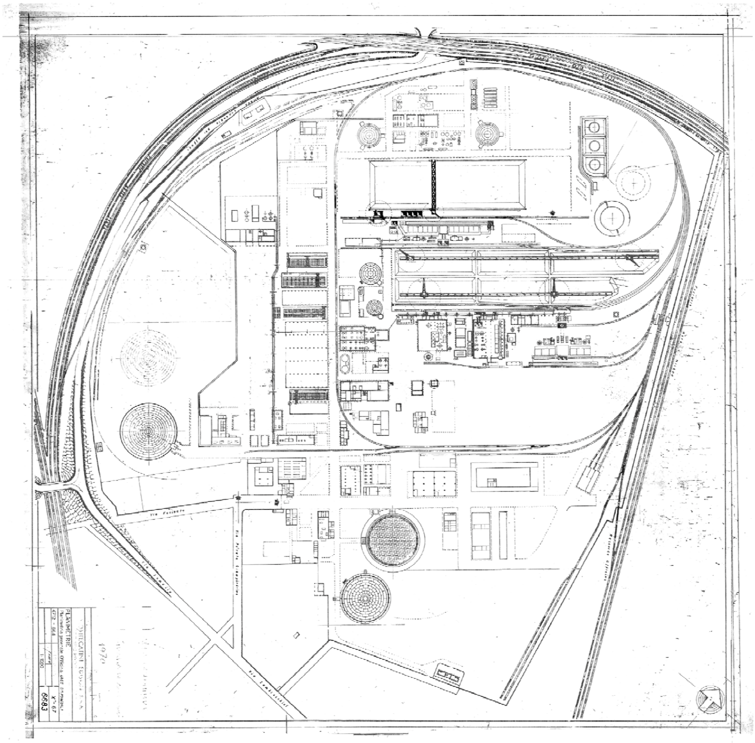

Figure 2. Scan of the general plan of the Gas Works, original transparency, 1970.

The novel ecosystem currently has no direct ecological connections with other green areas, due to the railways that surround it; however, it is configured as an important ecological site for the future creation of a large park along the urban ring. Near La Goccia are present other similar brownfields and spontaneous woodlands such as Cava Lucchini, to the east, and Parco Simoni to the north.

2.1.2. Social Issues and Design Developments in Recent Decades

Immediately after its abandonment, the area quickly became the subject of impactful urban projects. These projects, none of which were ever realized, alarmed the local community. Thus, a local Committee (Comitato La Goccia) in defense of the spontaneous ecosystem was formed in 2012, and in ten years organized numerous initiatives to publicize this novel ecosystem and defend it from uncontrolled urbanization. The main initiative took place between 2019 and 2020, when more than 30 artists agreed to donate one of their works to the forest, along a path laid out by the Committee activists. Considering the closure of the area due to soil contamination, the action was conceived as an act of civil disobedience, starting to make the novel ecosystem better known and to increase public awareness of its preservation.

In June 2021, a group of activists, professionals, and students organized a preliminary participative analysis of the novel ecosystem through citizen science to estimate the ecosystem services (ES) provided by the novel ecosystem of "La Goccia". As the artistic initiative described above, the participative analysis of the citizenship was carried out without permission from the authorities, despite the fact that the area was closed to the public. Given the political conditions and the existing conflicts between citizenship and municipality at that time, the action aimed at raising the level of discussion and the possibilities of launching a project for the protection, recovery, and valorization of the wild ecosystem. Through this study of the ecosystem, it has been possible to develop a collaborative pathway with the Municipality of Milan, which until then appeared unreceptive to the demands of citizenship.

In August 2022, the Municipality of Milan signed a cooperation pact with an interdisciplinary group of partner institutions. This agreement, called “Osservatorio La Goccia” has been stipulated for the purpose of conducting a preliminary study on the ecosystem and assessing its bioremediation potential.

This pact laid the foundations for the work described in the present study, which was then made possible thanks to national funding raised for this purpose.

At the same time, Politecnico di Milano, which owns of part of the area, presented the masterplan for the entire site, designed by the architect Renzo Piano, which envisages the preservation of a large wooded area to the North-East (the subject of the cooperation agreement), the construction of a service road around the forest and the development of the university campus in the southern portion.

At present, excluding the portions where the campus of the University Politecnico di Milano is currently planned, the novel ecosystem covers about 18 ha.

2.2. Overview of the Methodology

Professionals and researchers in the fields of botany, agronomy, microbiology, phytoremediation, zoology, pedology, and landscape architecture were involved, in order to build a collaborative pathway with the Municipality of Milan with the aim of preserving and enhancing the novel ecosystem, as well as for developing an experimental reclamation process through the application of NbSs starting from the existing wild urban woodland.

The interdisciplinary partnership of Osservatorio La Goccia, in the first phase of multilayer analysis, included a national research institute (IRET-CNR), two innovative start-ups (Terrapreta, M3R), two non-profit organizations (CFU-Italia Nostra, Progetto Natura), one university (Bicocca University of Milan), and the Natural History Civic Museum of Milan (MSNM).

This manuscript presents the main results from the first integrative ecosystem analysis, which was carried out within the collaborative agreement with the Municipality of Milan and subsequently on behalf of MM S.p.A., within the framework of the financing Decree ‘Foresta Urbana’. This last project enables the gradual and limited opening of the area to citizens, while phyto- and bioremediation techniques are applied as part of the reclamation project (Progetto Operativo di Bonifica—POB).

In order to fulfill the goals of this study, the following analyses were carried out during the exploration, study, and project development phases on the site. The subsequent sections provide a detailed description of each step of the analysis.

- Preliminary participative ES assessment (2021);
- Vascular flora and lichen surveys;
- Forest stand survey;
- Soil studies;
- Fauna surveys.

The above studies also served to assess the main regulating ES of the novel ecosystem. The target ES were as follows:

- Carbon storage and sequestration in biomass;
- Regulation of urban hydrology;
- Reduction in airborne particulate matter pollution;
- Increase in biodiversity at the species and ecosystem level

The carbon storage assessment was based on the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation. The assessment did not take into account the levels of soil carbon, nor the levels of carbon from dead vegetation.

2.3. Methods for the Preliminary Participative ES Assessment

The participative analysis was conducted in June 2021, using the functional tool iTree Eco V6.0.22 for the preliminary ES assessment. iTree Eco is designed to use standardized field data from randomly selected plots and local hourly air pollution and meteorological data to quantify urban forest structure and its various effects [40]. iTree Eco can be considered reliable to estimate important qualitative ecosystem functions, such as carbon storage and sequestration, reduction in surface runoff, removal of air pollution, or oxygen production. While other ES, such as the reduction in the urban heat island effect, are not yet calculable using this methodology.

Within the Bovisa-Goccia area, a 23.66-ha plot was selected following the administrative subdivisions and the physical limits of roads and perimeter walls, concentrating on the eastern and southern sides of the area, which are the most densely vegetated. Through the iTree Eco tool, a sample analysis was carried out: 25 circular plots, each with a diameter of 20 m over the study area were randomly selected, covering a total of 7850 m^2 (Figure 3).

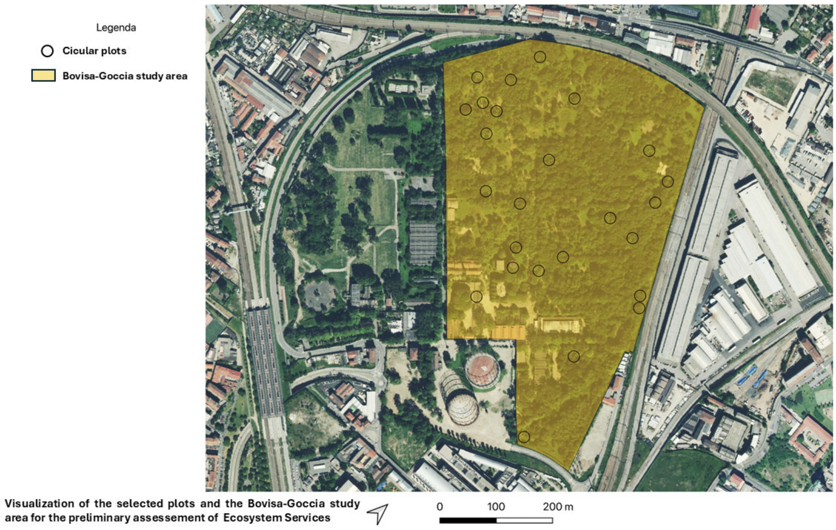

Figure 3. Visualization of the selected plots and the study area for the preliminary ES assessment, 2021.

The activities took place in June 2021, with the involvement of experts, the participation of students and citizens, and the coordination of a small working group. This participative analysis was carried out over a period of 5 days with the involvement of about 40 participants. During the mapping activity, the participants were divided into groups of four to five people and proceeded through the following process:

- Localization of the assigned plot using GPS;
- Positioning in the center of the plot and branching the cross of ropes to mark the diameters of the circle;
- Identification of trees with diameters greater than 7.5 cm within the circle;
- Data input on cards or directly into the iTree Eco app;
- Occasional registration of representative trees or stands of trees in the Curio app, even outside of the plots.

Within the groups, participants were divided with the following goals: assessing the species, health status, circumference and height of each tree surveyed, marking it with chalk, recording data, supervision (overview in order not to miss any trees or make duplicate surveys).

For each plot, a description was made, and the percentage of canopy cover, the percentage of shrub cover, and the percentage of ground cover types were recorded.

For each tree, the following parameters were recorded:

- Species;
- Stem diameter measured at 1.30 m from the ground;
- Estimation of the height;
- Percentage of healthy crowns.

During the data collection, the trees were identified at the most specific taxonomic level possible. Trees that were not identified to the species level have been classified by common name (e.g., ash).

2.4. Methods for the Vascular Flora and Lichen Surveys

A more specific floristic study was conducted following the ES assessment described in Section 2.3. The aim of this study was to gain insight into the vegetation composition of the area.

2.4.1. Vascular Flora

Floristic surveys were conducted during the years 2022, 2023, and 2024, from March to November. The identification of the taxa was carried out on the basis of the Flora d'Italia [41] and various specific monographs. The botanical nomenclature followed the checklist for native and alien vascular flora of Italy, continuously updated on the Portal of the Flora of Italy (http://dryades.units.it/floritaly/, accessed on 19 June 2025). Some specimens are still under examination, and further surveys are planned for the coming years.

2.4.2. Lichens

Lichen surveys took place in Spring 2023. Species identification was based on the online keys provided in ITALIC 8.0 [42] that was also used as a reference for nomenclature. The study was limited to epiphytic and epigaeic species; epilithic species will be eventually studied in future.

2.5. Methods for the Survey of the Forest Stand

2.5.1. Methods for the Analysis of Historical Photos

By accessing the main geoportals available on the web, various orthophotos of the area under examination were retrieved and subsequently imported into a GIS (Geographic Information System) environment. Using photo interpretation, the evolution of the green cover was estimated at three historical thresholds: 1975, 1998, and 2023, with respective quantification in ha of the area occupied by tree vegetation.

To calculate the change in canopy cover, digital pictographs were created by tracing the extent of the tree crowns for each orthophoto analyzed. The percentage of canopy cover was calculated based on the size of the study area (approximately 18 ha).

2.5.2. Methods for the Analysis of the 1994 CFS Forest Census

The first forestry study of the area is the one commissioned by AEM (Agenzia Energetica Municipale) to the State Forestry Corps (CFS) and edited by Alessandra Stefani in 1994. The analysis was carried out on 42 ha using the methods of the classic forestry census: tree stand count, cataloging the presence of each plant species across distinct diametric classes. tree stand survey of the plants present, subdivided by species and diametric classes. The work returned a technical report summarizing the data in tables as well as a cartography of the area showing the location of the main species.

The present study exclusively reports the primary outcomes of the 1994 tree census, with the objective of conducting a comparative analysis with subsequent forestry studies.

2.5.3. Methods for the Forest Census of 2024

The dendrometric campaign was conducted between January and February 2024 on 18 ha. The study of the forest compartment was developed in successive stages with the definition of the parameters to be surveyed, the production of basic cartographic drawings, the execution of the survey, the interpretation of the inventory data, and the drafting of the summary report. A total survey of the plants present was carried out with a minimum reference diameter threshold of "10" (minimum diameter at breast height equal to 7.5 cm). This means that for the determination of the quantitative parameters, all plants present with a diameter greater than 7.5 cm above ground at 1.30 m (Diameter at Breast Height, DBH) were surveyed. For each plant with DBH above 7.5 cm, the total number of stems, species, and diameter were recorded.

The number of stems was counted either as part of the survey, as well as the number of plant specimens, because many trees were 'polycormic', i.e., divided into several stems already at the collar (ground level), or below the diameter height threshold (1.30 m from ground level). Species were, in some cases, aggregated by genus in order to summarize the data.

In addition to the customary dendrometric parameters, the forest survey also qualitatively characterized the forest present. In fact, the surveyed plants were subdivided into viable, dead, decaying, and fallen, with the presence of lesions, fungal carpophores, and interference with artifacts. Subsequently, the heights of some clusters of plants were surveyed in order to construct the hypsometric curves (correlation curves between plant diameter and height) of the main species and to estimate the growing stock, i.e., the epigeal mass present within the forest.

The study area was subdivided following recognizable boundaries (roads, fences, channels, walls, artifacts, etc.) in order to create independent units on which to carry out plant census and forest characterization. A total of 31 plots were identified in the study area (Figure 4).

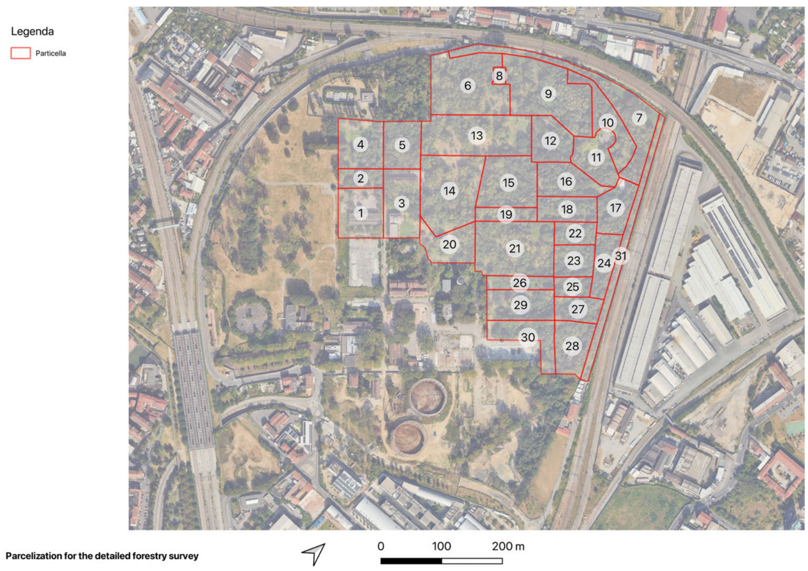

Figure 4. Parcelization for the detailed forestry survey, 2024. Numbers identify the homogeneous parcels in which the tree survey was conducted.

2.6. Methods for the Soil Studies

Various analyses were carried out on the state of the soils and sealings during 2024.

The study on the soils of the Goccia Forest had two main objectives: to map sealed surfaces; to describe and assess the physical and chemical characteristics of the soils.

2.6.1. Methods for the Sealed Surface Mapping

A significant portion of the soils in the area is sealed with asphalt, concrete, or cement. In some limited cases, sealing is due to rounded cobblestones, either bonded or loose (remnants of old cobbled paths). The survey involved walking across the entire area, checking for surface or shallow sealing layers, and consulting historical aerial photos, especially from 1975. Sealings were evaluated based on material type, alteration state, and the thickness of new soil forming above them.

2.6.2. Methods for the Soil Characterization

Soil sampling—100 points in total—was carried out using mechanical excavations or manual minipits, with a maximum depth of 50 cm. Soil profiles were described and sampled by pedological horizons (Soil Survey Staff, 2024), recording coarse fragment content, structure type, root quantity, and presence of artifacts. A total of 242 samples were collected. The fine earth fraction (<2 mm) was analyzed (Soil Survey Staff, 2014) to determine texture, pH, available phosphorus (Olsen method: extraction with $NaHCO_3$ 0.5 M), exchangeable potassium, carbonate content, organic matter, and total nitrogen. For each profile, results were weighted by horizon thickness to obtain average values for topsoil (0–20 cm) and the first subsoil (20–50 cm). Profiles were classified using the WRB international standard for soil classification system [43].

2.7. Methods for the Fauna Surveys

2.7.1. Methods for the Invertebrate Fauna Survey

Microarthropod samples were collected between October and November 2024, during peak activity of soil fauna [44]. Three soil samples (10 × 10 × 10 cm) were collected in each of 16 stations, located both in open (n = 6) and woody (n = 10) areas. The samples were placed in black fabric bags, labeled, and processed in the laboratory on the day of collection to maximize organism survival and extraction. Soil fauna was extracted using Berlese–Tullgren funnels, with an extraction period of 10 days. Microarthropods were mainly determined at the order level, counted, and separated following the standard biological soil quality methodology (QBS-ar) applied to microarthropods [44]. QBS-ar is an index based on the biological form approach and assesses the adaptation of organisms to an edaphic habitat, in relation to specific morphological characters (e.g., reduction or loss of pigmentation and appendages, thickness of cuticle). Using a standard table (QBS-ar) applied to microarthropods [44]. A score named ecomorphological index (EMI), which ranges from 1 (no adaptation to soil) to 20 (maximum adaptation to soil), is assigned to the microarthropod taxa. QBS-ar is thus the sum of the EMI scores of the microarthropod groups recorded in the sample, following the principle that the higher the number of groups well-adapted to the edaphic habitat, the higher the biological soil quality. Taxa are then classified as epi- ($EMI \leq 5$), hemi- ($5 < EMI \leq 15$), and eu-edaphic ($EMI = 20$), that is, those poorly, medium, and well-adapted to the soil environment.

Butterflies were monitored monthly, between April and September 2024 (excluding May for adverse meteorological conditions), for a total of five sampling dates, by visual observation combined with the use of an entomological hand net. A specialized operator counted all the individuals observed along a fixed transect, collecting data only under sunny conditions and with low wind intensity, between 10 a.m. and 5 p.m. According to

Pollard [45], only the observations made up to 5 m ahead and on both the operator's sides, and 5 m above the ground were recorded. Butterflies were identified directly in the field, by means of dichotomous keys, and immediately released.

2.7.2. Methods for the Vertebrate Fauna Survey

During the breeding season 2024, three bird censuses were conducted in early April, May, and June using the territory mapping methodology [46]. A specialized operator (ZP) walked a fixed transect within four hours of sunrise. All contacted birds were identified by sight and sound, distinguishing transient individuals from potential breeders. Reproductive status was determined based on behaviors (e.g., singing, nest-building, or feeding young). Collected data were used to estimate the total number of species, number of breeding species and minimum number of breeding pairs.

Bats were surveyed using a passive acoustic monitoring approach (PAM) [47]. An AudioMoth device was placed in a fixed location within Goccia Forest for three sessions during 2024, the first in Spring (May), the second in Summer (July/August) and the last in early Autumn (September), to cover the period of higher bat activity [48]. Recordings were automatically analyzed with Kaleidoscope and validated manually [49]. Additionally, potential roosting sites in trees and buildings were inspected once at dawn in August, to detect possible pre-entry "swarming" behavior [50].

Meso-mammals were monitored qualitatively using two camera traps [51], placed seasonally since 2022/2023.

3. Results

3.1. Preliminary ES Assessment of the Spontaneous Forest

In June 2021, within the 25 selected plots, a total of 509 trees were mapped.

In the 23.66 ha of reference, iTree estimated the presence of 16,300 trees, of which 53.4% have a diameter of less than 15 cm, highlighting an important forest renewal process from 1994. Density was estimated at 689 trees/hectare and canopy coverage at 74.9%. The economic value estimates generated by the iTree tool are not reported in this study.

The three most common plant species among the mapped plants were *Robinia pseudoacacia*, *Celtis australis* and, *Populus* spp.

Concerning regulating ecosystem services, the following indicators were estimated (Table 1).

Table 1. Regulating ecosystem services assessed for the Bovisa-Goccia area (23.66-ha plot) through the iTree Eco software., V6.0.22.

Ecosystem Service	Indicator	Unit of Measure	Amount
Carbon storage and sequestration in biomass	Carbon storage	Metric tons of carbon	3410
	Carbon sequestration potential	Metric tons of carbon per year	77.72
	Net carbon sequestration	Metric tons of carbon per year	67.12
Regulation of urban hydrology	Surface runoff reduction	Cubic meters per year	1780
Reduction in airborne particulate matter pollution	Air pollution removal (particulate matter less than 2.5 microns)	Metric tons per year	1.389

- Carbon storage: Trees in La Goccia are estimated to store 3410 metric tons of carbon. Of the species sampled, *R. pseudoacacia* stores and sequesters the most carbon, approximately 33.6% of the total carbon stored and 38.9% of all sequestered carbon.

- Carbon sequestration potential: The gross sequestration of La Goccia trees is about 77.72 metric tons of carbon per year. Net carbon sequestration in the urban forest is about 67.12 metric tons.
- Surface runoff reduction: Trees and shrubs of La Goccia help to reduce runoff by an estimated 1.78 thousand cubic meters a year. Avoided runoff is estimated based on local weather from the local designated weather station.
- Air pollution removal: It is estimated that trees and shrubs remove 1.389 metric tons of air pollution, such as ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter less than 2.5 microns (PM2.5), and sulfur dioxide (SO_2) per year. Pollution removal was greatest for O_3.

3.2. Vascular Flora and Lichens

3.2.1. Vascular Flora and Botanical Observations

During the floristic surveys, a total of 258 vascular plant taxa (species and subspecies) were recorded, belonging to 65 families and 174 genera. Of these, 199 taxa (77%) are native to Italy, 55 (21%) are alien, and 4 (2%) are cryptogenic. The alien taxa are distributed across 27 families and 41 genera.

Several native species of particular interest for the Milan area were observed, including *Cephalanthera longifolia* (L.) Fritsch (Orchidaceae), *Clinopodium vulgare* L. subsp. *vulgare* (Lamiaceae), *Phelipanche purpurea* (Jacq.) Soják (Orobanchaceae), *Pilosella piloselloides* (Vill.) Soják subsp. *piloselloides* (Asteraceae), *Polystichum setiferum* (L.) Roth (Dryopteridaceae), *Potentilla argentea* L. (Rosaceae), and *Saxifraga tridactylites* L. (Saxifragaceae). These findings highlight the role of the area as a refugium for flora of conservation interest, offering valuable habitat within the urban landscape [52].

Specific microhabitats contribute to this floristic richness. For example, walls of some buildings with dripping water host hygrophilous ferns such as *Adianthum capillus-veneris* L., *Asplenium adiantum-nigrum* L. subsp. *adiantum-nigrum*, *A. ruta-muraria* L. subsp. *ruta-muraria*, *A. scolopendrium L. subsp. scolopendrium*, and *A. septentrionale* (L.) Hoffm. subsp. *septentrionale*. In areas with more compact soils, species like *Saxifraga tridactylites* L. and *Draba verna* L. subsp. *verna* tend to dominate.

Among the alien taxa, several are considered invasive or potentially problematic due to their ecological impacts. These include *Acer negundo* L., *Ailanthus altissima* (Mill.) Swingle, *Ambrosia artemisiifolia* L., *Artemisia verlotiorum* Lamotte, Bidens frondosa L., *Buddleja davidii* Franch., *Ligustrum ovalifolium* Hassk., L. *sinense* Lour., *Parthenocissus inserta* (A.Kern.) Fritsch, and *Prunus serotina* Ehrh. All of these species, except *P. inserta*, are included in the Lombardy regional blacklist of alien species of concern (L.R. Lombardia 10/2008, D.G.R. n. 2658, 16 December 2019). Moreover, *A. altissima* is listed under EU Regulation No. 1143/2014, which addresses the prevention and management of invasive alien species at the European level.

The most species-rich families within the vascular flora comprise those belonging to the Asteraceae (37 taxa, 25 genera) and Poaceae (29 taxa, 20 genera), followed by Rosaceae (20 taxa, 10 genera), Fabaceae (13 taxa, 9 genera), Caryophyllaceae (11 taxa, 7 genera), and Brassicaceae (10 taxa, 8 genera). Among alien species, the families Asteraceae (9 taxa, 5 genera), Rosaceae (7 taxa, 4 genera), and Amaranthaceae (4 taxa, 2 genera) are the most represented (Figure 5).

In terms of life forms, the total vascular flora is dominated by hemicryptophytes (98 taxa, 38%) and therophytes (92 taxa, 35.6%), followed by phanerophytes (40 taxa, 15.5%), geophytes (17 taxa, 6.6%), and nanophanerophytes (10 taxa, 3.9%). Only one chamaephyte was recorded: *Sedum album* L. subsp. *album*. The life-form composition of alien taxa differs markedly: phanerophytes are the most common (21 taxa, 38%), followed by therophytes

(20 taxa, 36%), hemicryptophytes (9 taxa, 16%), nanophanerophytes (3 taxa, 5%), and geophytes (2 taxa, 4%).

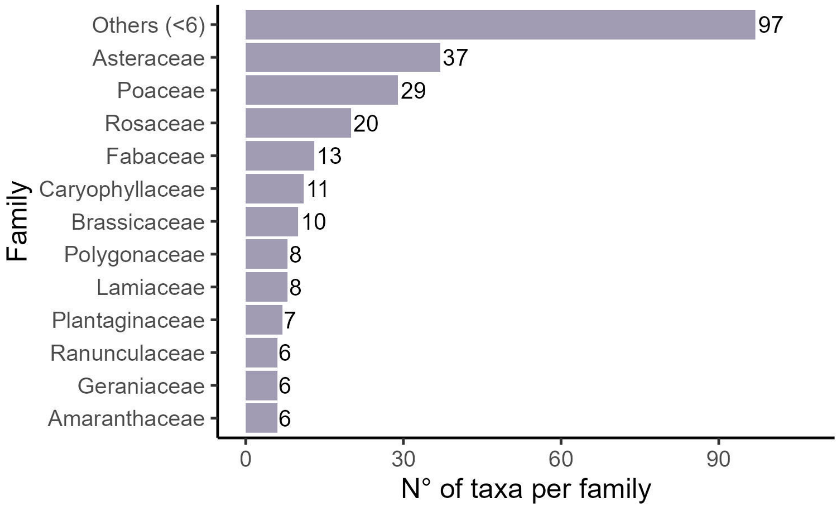

Figure 5. Families of vascular flora recorded in the Goccia forest, including the number of taxa for both total and alien species. In the 'Other (<6)' category are included all families for which we found less than six taxa.

The chorological spectrum of the total flora shows a prevalence of Mediterranean taxa (37 taxa, 14%), followed by Euro-Asiatic (31 taxa, 12%), European (29 taxa, 12%), and Paleotemperate taxa (29 taxa, 11%). Among alien species, nearly half are native to the Americas (27 taxa, 49%), while another 33% originate from Asia (18 taxa).

3.2.2. Epiphytic and Terricolous Lichen Biota

A total of 23 lichen infrageneric taxa were recorded, belonging to 18 genera, eight families, and four orders. Epiphytic taxa (21) account for 91% of this biota, whereas epigeic species (2) account for 9%. All are native to Italy.

Physciaceae (six taxa, five genera) and *Teloschistaceae* (four taxa, three genera) are the richest families, followed by *Candelariaceae* (three taxa, two genera), *Lecanoraceae* (three taxa, three genera) and *Ramalinaceae* (three taxa, two genera), whereas *Cladoniaceae* (two taxa, one genus) and *Catillariaceae* (one taxon, one genus) are the poorest. *Lecanorales* (10 taxa, 5 families) and *Caliciales* (6 taxa, 1 family) are the richest orders, whereas *Teloschistales* (4 taxa, 1 family) and Candelariales (3 taxa, 1 family) are the poorest.

The main growth form is the crustose (12 species, 52%), followed by the foliose (9, 39%), and the fruticose-composed growth form, typical of *Cladonia* accounts for only a minor part (2, 9%). Reproductive strategies are almost perfectly balanced: 12 species (52%) reproduce mainly asexually by means of soredia, 11 (48%) sexually by means of spores.

Most of the recorded species are widespread in Italy and not rare, even in highly human-impacted areas [42]. The most interesting epiphytic species is *Parmotrema perlatum* (Huds.) M. Choisy, which, although not uncommon in lowlands, is usually absent from urbanized areas. Another interesting finding is *Bacidina adastra* M. Hauck and V. Wirth, which was found for the first time in Lombardia in La Goccia and had been reported before in Italy only from Emilia-Romagna [53]. Remarkable is the occurrence of two *Cladonia* species, i.e., *Cladonia chlorophaea* (Sommerf.) Spreng. and *Cladonia* rei Schaer., in the dry grassland patches established in the clearings of the woodland. They are typical of such habitats, with the closest occurring sites known so far located in the Ticino river valley [54].

3.3. Progression of a Post-Industrial Forest

The aerial photos from 1975, 1998, and 2023 were considered the most representative for visualizing the progression of the novel ecosystem. (Figure 6).

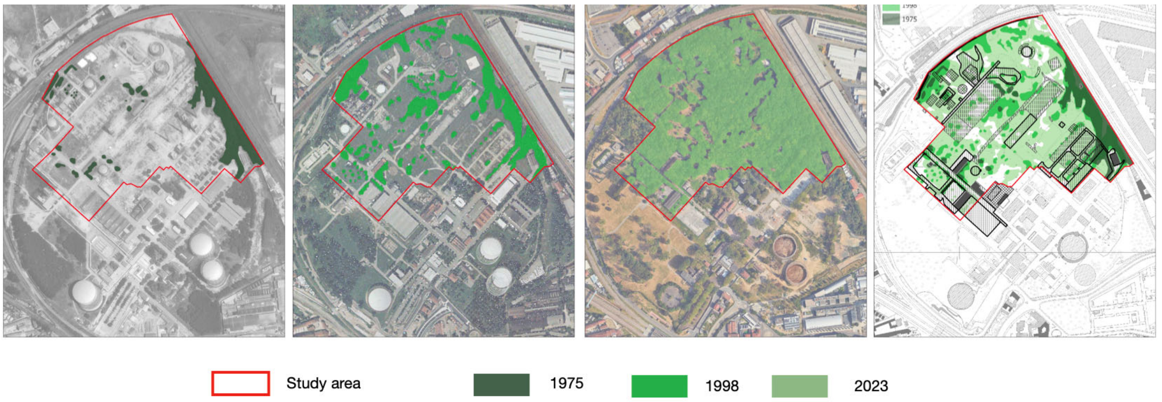

Figure 6. Visualization of the evolution of the Bovisa–Goccia forest, across historical thresholds (Italia Nostra survey, 2024). From left to right: forest cover in 1975, 1998, and 2023, respectively. The final picture on the right presents the superposition of forest cover layers, corresponding to the three years considered in the study.

Despite parts of the gas works still being active in 1975, there was already a dense area of spontaneous forestation on the south-eastern edge along the railway wall. Over the following 23 years, canopy cover doubled, while from 1998 to 2023, the 25 years following the dismantling of the workshops, canopy coverage increased by 335%.

3.4. Analysis of the Data from CFS Forest Census (1994)

During the CFS forestry census in 1994, a total of 2049 stems were recorded within an area of 42 ha. Of these, 898 were located in rows along the railway walls and in flower beds. The forestry study included the trees newly planted by the last operator (A.E.M.) in various parts of the area, particularly the wooded patches with prevalence of *Populus nigra* to the south and west, and the irregular mesh in the north-central area.

The most represented species in numerical terms was the *Robinia pseudoacacia* (43.9%), followed by *Populus* spp. (14.01%), *Platanus* spp. (13.47%), *Acer* spp. (6.34%) and *Betula* spp. (5.81%) and *Celtis australis* (3.42%). Of the trees surveyed at the time, 46% had a diameter of less than 22 cm. However, the study also revealed the presence of trees with diameters greater than 48 cm, accounting for 7.61% of the total. These constituted the oldest part of the forest's tree stock and included mainly locust trees, plane trees, poplars, maples, and birches, as well as specimens of hackberry and paulownia.

The study highlighted an overall good plant's health, even from a static point of view. It did not mention any problems related to the presence of the underlying slab and sealing, probably because, at that time, the number of naturally occurring plants was still rather limited. The 1994 forestry report highlighted the presence of "important tree vegetation, generally in good vegetative and static condition" covering 6 ha of the 44 ha surveyed. The report emphasized the presence of tall trees and in the final pages read: "The tree stand in Bovisa consists of a considerable group of trees, [. . .] in harmony with the climatic aspects of the Po Valley area and, on the whole, resistant to the adversities of the urban environment. Organized in groups and rows, with some elements of high esthetic value, they constitute a heritage of the highest interest for a city like Milan". Following the decommissioning and abandonment of the industrial site, the spontaneous ecosystem experienced a long period of growth and tree densification, as shown in the previous sub-chapter.

3.5. Forest Qualitative Overview—Italia Nostra Survey (2024)

The forest is characterized by the presence of numerous species from different time periods: the trees that existed before the abandonment of the area and the newly established trees.

Some of the already existing trees are confined in beds and large plants cultivated with the techniques of ornamental greenery until at least the early 1990s: these include especially *Poplar* spp. and *Celtis australis*, an isolated group of *Tilia americana*, and individual specimens of *Platanus* × *acerifolia*, *Paulownia tomentosa*, *Ficus carica*, and *Junglans regia.*

With the exception of *Ulmus* spp., all the tree species had already been surveyed in the 1994 CFS's survey. A lower occurrence of *Acer* and *Betula* was found in relation to previous censuses, mainly due to different extensions of the study area.

The dominant species today in terms of numbers are *C. australis* and *Robinia pseudoacacia*, which are highly represented in the lower diameter classes (Ø 12.5 cm to 17.5 cm), i.e., in classes that have the potential to shape the future evolution of this forest, provided that growth conditions are favorable. This is followed by *Populus* spp. and *Ulmus* spp., faster-growing plants with several specimens in the medium (Ø 17.5 cm to 32.5 cm) and large (Ø > 32.5 cm) classes.

Between *Robina* and *Celtis* trees, a significant numerical difference was highlighted in favor of the *Robinia* in the medium and large class plants, which includes mother trees (Simard, S.W., 2017) along the ancient tracks in the eastern part of the forest (Figure 7). However, the most distinguishing factor between the two species is the extent of vegetative compromised condition observed in *R. pseudoacacia*, in contrast to the favorable conditions recorded for *C. australis*, suggesting an ongoing process of forest succession.

Figure 7. One of the oldest *R. pseudoacacia* mother trees within the forest.

The forest density exhibited significant variability (Figure 8). The area is characterized by a transition of vegetation layout, from dense areas with old trees, to dense stands of spindly trees, to sparse areas of bramble cover or grass that are subject to the progressive establishment of shrub species.

Over the years, spontaneous vegetation has colonized almost every substrate typology, including sealed surfaces, with different densities and types of plants. In fact, in some cases, the tree cover is rare and discontinuous, and asphalt or concrete is clearly visible at the bases of the plants that have penetrated the asphalt fissures. In other locations on surfaces such as concrete, the seal is covered by an organic substrate comprising grass, soil and leaves measuring several centimeters on which herbaceous species, shrubs and trees vegetate.

Legenda

Tree density

- 0–0.02
- 0.02–0.04
- 0.04–0.06
- 0.06–0.07
- 0.07–0.08

N	Sqm	Total trees	Density
1	6,102	23	0.004
2	2,379	82	0.034
3	6,893	133	0.019
4	5,967	85	0.014
5	4,835	221	0.046
6	12,006	537	0.045
7	8,737	549	0.063
8	5,70	26	0.046
9	12,820	566	0.044
10	6,565	210	0.032
11	5,037	181	0.036
12	4,672	225	0.048
13	13,816	321	0.023
14	10,578	305	0.029
15	7,073	547	0.077
16	5,184	294	0.057
17	4,497	298	0.066
18	4,065	265	0.065
19	2,303	108	0.047
20	4,856	170	0.035
21	11,641	452	0.039
22	3,480	205	0.059
23	2,580	199	0.077
24	3,727	249	0.067
25	2,071	164	0.079
26	3,760	145	0.039
27	3,077	166	0.054
28	5,016	261	0.052
29	4,324	222	0.051
30	4,924	183	0.037
31	4,999	168	0.034

Planimetry of Tree density

Figure 8. Planimetry of tree density (number of trees per square meter).

3.6. *Forest Specific Composition and Ongoing Ecological Succession*

A total of approximately 9000 stems were surveyed out of a total of 7563 plants, considering polycormic trees.

The distribution of species shows the dominance of *Populus* spp. in the north-western and central part of the area, near the roads where rows were planted, while *Robinia pseudoacacia* is mainly located in the east part and *Celtis australis*, *Ulmus* spp. and Prunus spp., together with shrub species such as *Sambucus nigra* and *Crataegus monogyna*, follow a more random and diffuse distribution.

The species numerically most present are therefore *Robinia pseudoacacia* (40.9%), *Celtis australis* (29.0%), *Populus* spp. (9.6%), *Ulmus* spp. (7.9%) and *Ailanthus altissima* (3.4%) (Table S1, Supplementary Materials).

Considering the entire stand of 7560 plants, 65.1% are small plants belonging to the lower diameter class (10–15 cm), 28.9% are medium diameter plants (20–35 cm), while 6% are large diameter plants (>35 cm). When considering 'live' plants, *Celtis australis* becomes the most represented species (37.4%), followed by *Robinia* (30.3%), *Ulmus* (9.1%), *Populus* (8.6%) and *Ailanthus* (4.2%), as it is shown in Table S2 (Supplementary Materials) and is clearly visible in Figure 9 that shows the prevailing species for singular plots in relation to living trees.

This indicates the poor plant's health and the regression of *Robinia* and *Populus*, to the advantage of *Celtis australis* (hackberry) and *Ulmus* spp., both of which are able to establish themselves between buildings and soils sealed by asphalt. *C. australis*, that is mostly represented by young plants, is confirmed as the species that is best adapted to the disturbed soils of the Goccia area; in fact, only 3% of the hackberry trees are in a decaying state and only 1% are dead. It was then observed a marked ability of the *C. australis* to establish itself in sealed areas, on the edges of artifacts, thanks to its mighty roots that provide it with stability. Evidence has been found in various locations within the ecosystem to suggest that *Celtis* is replacing *Robinia*. It is reasonable to think that its spread is mainly due to dissemination by bird droppings, especially from the species that feed on its seeds in the spring and summer months. This dynamic emerges from the observation of stands of young hackberry trees at the foot of tall light poles or large *Populus* or *Robinia* trees (Figure 10), where birds usually stand.

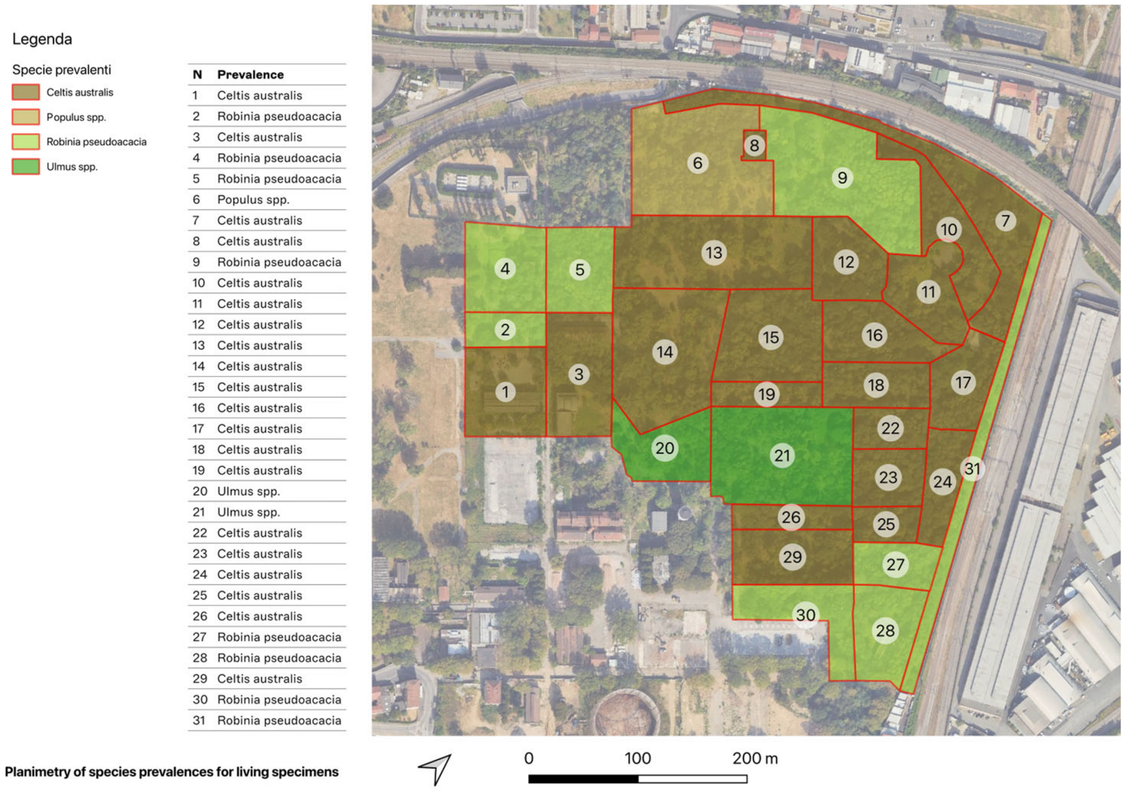

Figure 9. Planimetry of species prevalence for living specimens.

Figure 10. Several stump shoots of *C. australis* surround an old *R. pseudoacacia* tree.

Regarding the invasive species *Ailanthus altissima*, a total of 242 living specimens with DBH greater than 7.5 cm were surveyed. Its distribution on the site represents 3.4% of the total number of plants, without considering the phytosanitary state. Figure 11 shows that its distribution is being concentrated in some marginal areas of the study site.

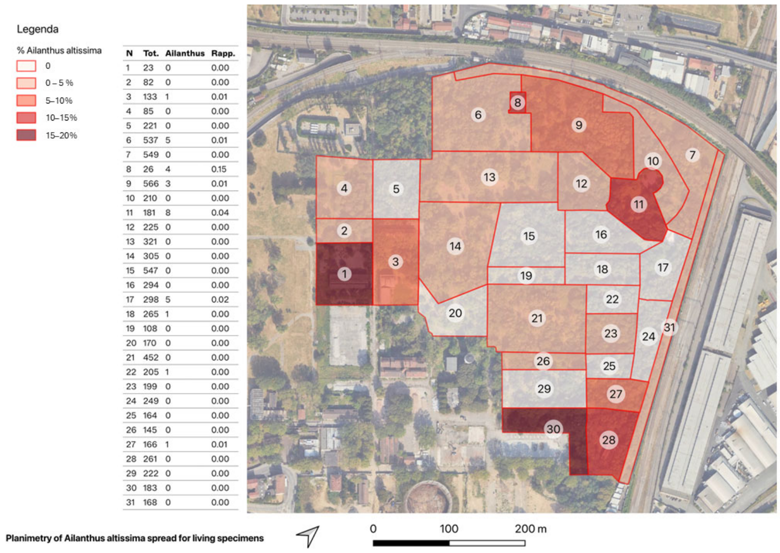

Figure 11. Planimetry of *Ailanthus altissima* spread for living specimens.

3.7. Soil Characteristics

3.7.1. Sealed Surface Mapping

A first map of sealed surfaces was produced (Figure 12), showing that at least approx. 28% of the Goccia area is sealed (roughly half asphalt, half concrete). Where the technical map indicates the presence of buildings and platforms, vegetation has now completely covered all evidence of continuous sealing. It is therefore assumed that the extension of terrain with artifacts from demolitions is greater than indicated on the map. The old concrete water pipes to the north-east of the site are not included in this categorization.

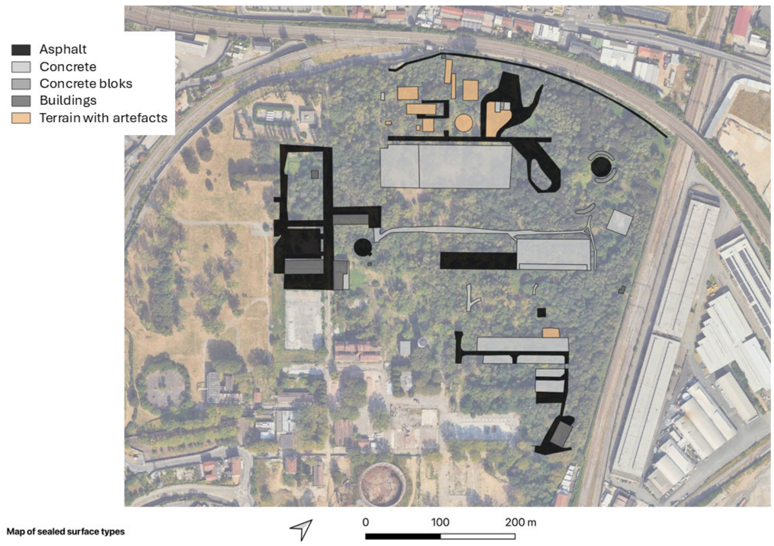

Figure 12. Map of sealed surface types.

The sealing layer (Figure 13) is often undergoing alteration and fragmentation, especially when asphalt is involved, due to tree roots growing beneath and expanding, which leads to cracking (Figure 14). These cracks are then colonized by other plants, gradually breaking up the sealing in a slow “natural desealing” process. In the case of concrete covers, the process is slower, but locally there are fractures due to the enlargement of the stumps or uprooted trees that had established in cracks. New soil is forming above the sealing layers, mainly due to decades of organic matter deposition (leaves, twigs, fruits) from the overlying vegetation. The thickness of this new soil can exceed 10 cm in some cases.

Figure 13. Soil sealed by asphalt and concrete. On the left, the roots in the sealed soil come from trees growing by the roadside. On the right, the removal of the fertile layer (topsoil) and the addition of a subgrade are clearly visible, leaving only the mineral soil substrate in evidence.

Figure 14. *Ulmus* spp. root action in the fragmentation of the asphalt surface ("natural desealing").

3.7.2. Soil Characterization

The soils in the Goccia area are generally coarse or very coarse-textured: sandy loam predominates, followed by loamy sand, especially at depth. Fine-textured classes are virtually absent, with clay content very low and sand content often reaching 60%–80% (Figure 15).

Total carbonate content is low and never exceeds 10%.

Soil pH in water ranges widely, ranging from strongly acidic to alkaline (Figure 16). The distribution is skewed toward acidic values, confirming the limited presence of carbonates. Deeper layers can reach subalkaline values, while surface layers tend to remain neutral.

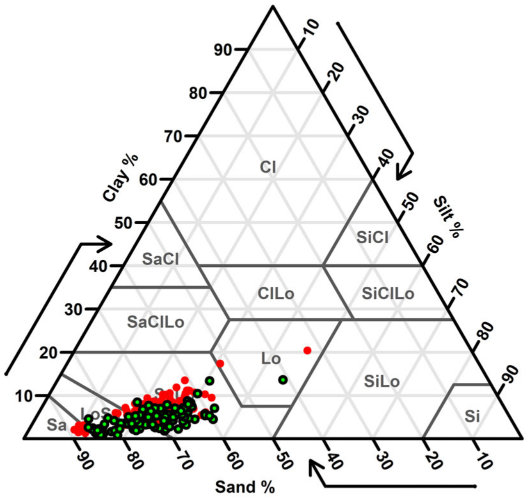

Figure 15. Texture data on the USDA soil-texture triangle: green points represent the 0–20 cm layer samplings; red points represent the 20–50 cm layer samplings.

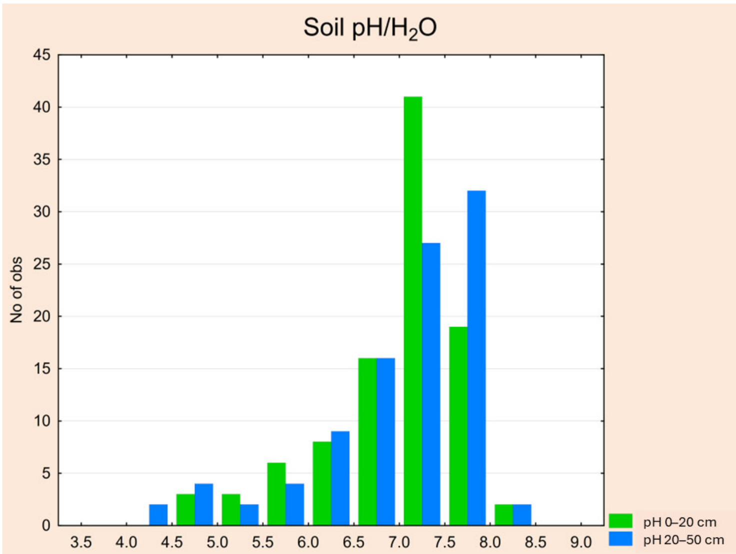

Figure 16. Frequency distribution of pH values in H_2O in the topsoil (0–20 cm) and in the first subsoil (20–50 cm).

Organic carbon data, compared to total nitrogen content, often indicate non-standard organic matter. Carbon to nitrogen (C:N) ratios above 50 suggest nitrogen-poor organic matter with significant amounts of fossil carbon or black carbon. Inert carbon may exceed 80% of total organic carbon. After correcting for inert C, the average organic carbon content is about 5%, with slightly higher values in the topsoil.

Exchangeable potassium, a key plant nutrient, averages 60–80 mg/kg, slightly higher in the surface layer. When compared to the CEC (cation exchange capacity, estimated on the basis of organic matter and clay content), values are slightly above 1%.

Available phosphorus (Olsen method) is rarely very low, with a modal value of 15 mg/kg, and often considerably higher.

From a taxonomic point of view, at least three major soil types are present: mostly disturbed Anthrosols (mainly Skeletic), some Skeletic Cambisols retaining features of the former agricultural soils, and Technosols in cases of heavy disturbance (especially with high artifact content). Sealed soils are classified as Ekranic or Thyric Technosols.

Currently, based on morphology and analytical data, the following general considerations on the agronomic and silvicultural fertility of Goccia soils can be made:

- Coarse fragments: Almost always present, often abundant (35%–70% by volume) or very abundant (>70%). Excess coarse material reduces the fine earth fraction, decreasing water retention and nutrient availability.
- Texture: Mostly coarse or very coarse, which does not hinder vegetation. Water infiltration is likely good, but water retention is limited, especially with high coarse fragment content.
- Reaction: Generally, not problematic for vegetation; the most common pH class is neutral. Some soils reach strongly acidic values (minimum measured pH 4.3), which could affect phytoremediation choices. Low pH also indicates reduced biological activity.
- Carbonates: Total carbonates are absent or scarce, posing no problems for vegetation.
- Organic matter: Across the full 50 cm sampled depth, the average organic carbon (corrected for inert C) is about 3.5%, equivalent to ~7% organic matter. These high values likely reflect the soil's history and vegetative contributions, particularly in the topsoil where organic matter exceeds 10%. Such levels support biological activity and fertility, especially considering pH conditions. Inert or black carbon is often high—sometimes more than in Milan's urban soils [55]—but should not hinder vegetation.
- Potassium: Exchangeable K is low by agricultural soil standards.
- Phosphorus: Available P is good to excellent (some soils > 100 mg/kg), likely due to previous land use and contributions from spontaneous vegetation.

3.8. Animal Biodiversity

3.8.1. Invertebrate Fauna

More than 9400 organisms, belonging to 18 taxa, were extracted from the soil samples (Table S3, Supplementary Materials). The dominant taxa were Acari and Collembola, representing about 51.5% and 29.3% of the total community, respectively. On average, QBS-ar were equal to 184 (min. = 143, max. = 221) and 205 (min. = 192, max. = 232) in woody and open areas, respectively. The values are indicators of good biological quality, being clearly above the threshold of 93.7 proposed by Menta et al. [56]) to separate high-quality soil from poor ones, and in line with the results of other studies carried out in forests and pastures [57–59]. The number of taxa, including eu-edaphic forms, was equal to 10 both in woody and open stations (Acari, Collembola, Coleoptera, Chilopoda, Diplopoda, Diplura, Symphyla, Pseudoscorpionida, and Protura e Pauropoda), even if, on average, slightly higher in open (media = 7.5, min. = 7, max. = 9) than in woody (media = 6.7, min. = 5, max. = 8) areas. These results highlighted the important role that also open areas play in the maintenance of soil biodiversity [57].

A total of 20 butterfly species (*Lepidoptera*, *Papilionoidea*), belonging to five families, were recorded (Table S4, Supplementary Materials). The most abundant species was Pieris rapae (n = 84), followed by Polyommatus icarus (n = 59), Polygonia c-album (n = 31), *Ochlodes sylvanus*, and *Celastrina argiolus* (n = 30). Most individuals were collected in/around patches of open areas. All the species present a wide distribution and are recorded as Least Concern (LC) in The Red List of Italian Butterflies [60].

3.8.2. Vertebrate Fauna

A total of 26 bird species were recorded, 20 of which (potentially or certainly) were breeding in the study area. The most abundant breeder was the blackcap (*Sylvia atricapilla*) with 10 estimated pairs, followed by the great tit (*Parus major*, four pairs), the blackbird (*Turdus merula*), and the wood pigeon (*Columba palumbus*), with three pairs each (Table S5, Supplementary Materials).

Acoustic sampling confirmed three bat species: Kuhl's pipistrelle (*Pipistrellus kuhlii*), Savi's pipistrelle (*Hypsugo savii*), and serotine bat (*Eptesicus serotinus*). These three species are widely spread in Italian urban contexts [61]. Camera traps detected three mesomammals: the gray squirrel (*Sciurus carolinensis*), the eastern cottontail (*Sylvilagus floridanus*), a likely Norway rat (*Rattus* sp.), and the native red fox (*Vulpes vulpes*). Droppings of the European hedgehog (*Erinaceus europaeus*), a steadily declining species [62], were also found (Table S6, Supplementary Materials).

4. Discussion

Our study provides a comprehensive assessment of the ecological dynamics of the La Goccia novel ecosystem and is opening the way to knowledge of the specific conditions required to sustain phyto- and bio-remediation processes in urban contexts starting from spontaneous nature.

The multi-layered approach allowed us to generate a wide understanding of the La Goccia Forest ecosystem beyond the singular biotic and abiotic layers. The study area hosts diverse vegetation, with an ecological succession that started more than 40 years ago and still occurs today, involving species that are best adapted to specific coarse soil conditions.

The area's unique microhabitat conditions promoted the establishment of notable lichen and herbaceous plant communities. This complex ecosystem has developed on highly contaminated and disturbed soils, confirming spontaneous Nature's ability to regenerate rapidly even in the hostile and densely urbanized context of the Milan metropolitan area [39]. Furthermore, this ecological process was supported by zoonotic seed dispersal, which contributed to the formation of the current forest ecosystem, now home to a variety of native vertebrate and invertebrate animal species.

The multi-layered approach we used emphasizes the need for integrated and process-based understandings of qualitative data that recognize the abundance and unpredictability of nature in urban contexts [23,26,63,64], as a step forward from static valuation tools traditionally utilized for ES assessment. Our study demonstrated that the area supports various ES. Additionally, other ES can be inferred from the ecological components analyzed. Further ES are expected to emerge once the area becomes partially accessible to the public.

This context set the basis to continue the experimental NbSs project design, which has the principal goal to preserve and possibly enhance the ES provided by the ecosystem. The application of the NbSs also has the burden of functioning within the restricted Italian regulatory framework: this requires a synergy between landscape, functional, and reclamation purposes, to allow a gradual public use and to set up a future participatory forest management, while reclamation is still in progress.

4.1. Forest Characteristics of the Novel Ecosystem and Related ES

From a forest succession point of view, the main species that must be taken into consideration among the recorded specimens are as follows:

- *Robinia pseudoacacia*, a species now naturalized in the reference territory [65], has numerous mother trees within the forest. This species, belonging to the Fabaceae family, through rapid growth cycles, has certainly improved soil fertility [66], allowing the development of forest biodiversity.
- *Celtis australis* has demonstrated remarkable resistance to the uneven, sealed soils prevalent on the site and is the most representative of the healthy tree specimens.;
- *Popolus nigra* or spp., is represented in the study site by some of the oldest specimens. However, it shows a lower capacity for renewal, as well as a greater exposure to disease, degradation in wood, and damage from strong winds.

- *Ulmus* spp., its distribution in the study area confirmed the characteristics of this species to adapt to any terrain, showing a great renewal capacity.

The distribution of *Ailanthus altissima* was found to be concentrated in the marginal areas of the study site. This demonstrates that the biodiversity of the ecosystem has been capable of preventing the establishment of this species.

Considering that the southeastern *R. pseudoacacia* grove was already present in the 1950s and that other plantations were carried out shortly before its abandonment in 1994, the ecosystem of La Goccia forest has reached a state of functional biodiversity [67] thanks to the combination of native and alien or invasive species [68]. This balance has also resulted in the preservation of relics of lowland forests and the presence of some plant species very rare for the urban environment (e.g., *Cephalanthera longifolia* and *Cladonia rei*).

Observing the evolution of the novel ecosystem of La Goccia forest, we can conclude that the tree plantations established on degraded sites, as the one that occurred on the study site in the 1990s, can act as successional catalysts by facilitating the recolonization of native vegetation, as reported also by other authors in that period [69–71]. These plantations, such *as Populus*, *Robinia*, *Acer*, and *Celtis* observed in La Goccia, accelerated the natural regeneration process by influencing the understory microclimate and soil fertility [11]. They also suppressed dominant grasses and attracted seed-dispersing animals. For forestry and animal biodiversity improvement, the growth of native species present with scattered specimens in the forest, such as *Prunus avium*, *Fraxinus ornus*, *Alnus glutinosa*, or *Acer campestre*, might be encouraged [72].

Whereas it is still evolving and young, the forest established in the area is already contributing to various ecosystem services such as carbon storage, carbon sequestration potential, surface runoff reduction, air pollution removal, and sustaining biodiversity. Furthermore, other ES, such as mitigating the urban heat island effect, whereas not directly identified by the present study, are already provided by La Goccia Forest [73]. Once the area is made accessible to the public in accordance with the plan, it will also contribute to human well-being by offering the recognized recreational and psychological benefits of exposure to wooded vegetation [74,75].

Beyond the quantitative results, the preliminary ES assessment made the Municipality of Milan realize the value of the Goccia's spontaneous ecosystem, leading the administration to sign the three year cooperation agreement "Osservatorio La Goccia" for the scientific study and monitoring of biodiversity in the area. Thanks to this collaborative process, the spontaneous ecosystem can now be understood as a laboratory for the experimentation and implementation of NbSs for soil remediation and for soil and biodiversity protection.

4.2. Framing Soils and Sealing Aspects

In general, the Goccia soils have been deeply modified by human activity.

Originally agricultural, they shared typical features of this plain area: deep soils on gravel and sand (fluvioglacial deposits), loose texture, subacid reaction, and moderate organic matter content. While some of these traits persist, the transition to industrial use has introduced significant and visible changes. In addition to the sealing, there have been physical changes (coarse foreign elements, such as cement and asphalt fragments, have altered the grain size) and especially chemical changes (coal dust residues, as well as black carbon, have profoundly altered the organic component; and all this without considering the increased levels of inorganic and organic soil contamination).

The disturbance level is evident in taxonomic terms: while pre-industrial soils were Cambisols, the area is now mainly Anthrosols, and in heavily disturbed zones, Technosols. Relatively unmodified soils are found mainly in the northern part of the Goccia, farther from industrial installations.

Spontaneous vegetation, especially forest species, is slowly modifying the soils, partially restoring more natural conditions: increased high-quality organic matter, improved structure, and acidification. On average, Goccia soils are capable of providing multiple ecosystem services: productivity, organic matter storage [76], and rainwater infiltration. Main soil issues include (i) contamination by heavy metals and organic pollutants; (ii) excessive coarse fragments; (iii) anthropogenic materials (brick, concrete, slag, coal dust, plastic, metal residues); (iv) sealing by cement, asphalt, or cobbles, found mostly near the surface (under a few cm of new soil) or at depth, buried by subsequent deposition.

The natural desealing process observed in the Goccia area is highly relevant to urban desealing discussions. Spontaneous vegetation is gradually fragmenting certain types of surface cover.

It would be interesting to test whether this process could be accelerated through artificial incisions. Similarly, experimental desealing efforts could assess the most appropriate vegetal species to plant following sealing removal for the improvement of the underlying layer. The newly forming soil above sealing layers also warrants attention: its properties will be assessed, and the development and root colonization of organic horizons will be studied.

4.3. Fauna Mediated Ecosystem Services

Considering the extremely disturbed context of the study area, the soils appeared to be of good quality in terms of edaphic communities, with high QBS-ar values and the presence of taxonomic groups well adapted to subterranean life. These communities benefit from the mosaic state of the forest, where several clearings are present. Such a configuration also likely promoted butterflies, which were mainly observed in open areas and along edges.

Whereas the bird species composition detected was similar to the one of Milan urban parks and green areas (Porro et al., in prep), the potential breeding of the European robin (*Erithacus rubecula*) and the Eurasian jay (*Garrulus glandarius*) and certain nesting of the green woodpecker (*Picus viridis*), three rare species in the city of Milan, stresses out the unicity and importance of the area from a conservation perspective. Same goes for mammal species like the declining European hedgehog and serotine bat, for which suitable urban habitats appear to be key for their conservation.

The fauna of La Goccia forest contributes to a wide array of ecosystem services. Bat species, on the other hand, play a key role in pest suppression [77], including mosquitoes, which are particularly preyed upon in an urban context [78]. Butterflies, even if to a lesser extent than bees, are considered good pollinators, especially in terms of long-distance pollen transfer, with important genetic implications for plants [79–81]. Soil fauna is involved in several soil processes and functions, contributing to regulate, among others, soil fertility, carbon sequestration, and pest abundances [82]. Other ES are going to be provided once the area is going to be accessible to local citizens: being exposed to a high diversity of butterflies and songbirds has been shown to improve the psychological well-being of people [83]. Similarly, among sampled mammals, foxes and hedgehogs have been reported to be highly appreciated by citizens [84].

La Goccia forest also hosts a few species which have been mostly linked to ecosystem disservices, such as the feral pigeon (*Columba livia domestica*), the hooded crow (*Corvus cornix*), and the invasive monk parakeet (*Psyttacula krameri*), gray squirrel, eastern cottontail, and *rattus* sp. The presence of these species is unavoidable given the urban context where the study area is located. Importantly, not all these species are necessarily unequivocally harmful; for example, gray squirrels and monk parakeets, besides their invasive status, are strongly appreciated by a consistent portion of citizens (Porro et al., in prep).

4.4. NbSs for Enhancing the Reclamation Potential of Novel Ecosystems

Drawing upon the findings of the multilayer analysis conducted on the wild urban forest, it is possible to identify elements that have the potential to be valorised, with a view to increasing the natural remediation capacity of the existing ecosystem. Among the tree species present in the La Goccia forest, the *Populus* spp. are certainly the most studied for phyto-technological applications, due to their characteristics of rapid growth, extensive root system, and high evapotranspiration potential [85,86]. *Robinia pseudoacacia* and *Celtis australis* have been less studied but are worth studying because of the rich microbiome inhabiting the rhizosphere of *R. pseudoacacia*, which characterizes the *Fabaceae* family [66], and the rapid growth and resilience to air pollution and drought stresses exhibited by *C. australis* [87,88].

Regarding herbaceous plants, the presence of several species belonging to the *Brassicaceae* family, and individuals of *Buddleja davidii*, indicates a good potential for phytoextraction of heavy metals [89,90]. Furthermore, the evolution of the wild ecosystem resulted in the formation of new soil, characterized by a high content of organic material. This development can be regarded as a fundamental starting point for a phyto- and bioremediation intervention. The role of this organic material is twofold: firstly, it serves as a growth substrate for plants, fungi and bacteria; secondly, it is capable of reducing the mobility and bioavailability of organic and inorganic contaminants, thereby attenuating their toxicity.

The present study constitutes only a preliminary survey of a complex ecosystem, yielding results that have opened new research perspectives. Indeed, in order to implement NbSs for the soil remediation of La Goccia Forest, it is imperative to enhance our comprehension of the ongoing remediation processes in the plant–microorganism system. The novel ecosystem has evolved over time, with plant species, fungal, and bacterial strains being selected to thrive in this degraded environment. Concurrently, biochemical processes are ongoing to reach natural homeostasis. These processes, known as "natural attenuation", can be enhanced by bioremediation and phytoremediation techniques [91]. In order to implement these techniques, it is of paramount importance to preserve and leverage the existing ecosystem [92]. Only through a comprehensive study to understand the ability of present species in absorbing, taking up, or excluding contaminants, and through a deep study of the microbiological communities of the rhizosphere, will be possible to correctly apply the aforementioned techniques, optimizing the natural remediation potential of La Goccia ecosystem and providing related ES [93].

Finally, beyond its unique environmental parameters, an important point of strength of La Goccia forest is the presence of an engaged community in the neighborhoods. This last element is pivotal in implementing successful NbSs for site remediation, in which decision making is a social and political process informed by scientific and technical information, rather than a science- or technology-driven process [94].

4.5. Overview of the Ongoing NbSs Project and Future Perspectives

The project is underway thanks to the initiative of the City of Milan and under the operational management of MM Spa. Osservatorio La Goccia is a large partnership that is working both under the decree law "Foresta urbana" and EUI.IA 02-130 "GOCCIA" project.

The goal of the project is not solely the removal of contaminants and the reduction in risk, but also the enhancement of the comprehensive benefits that are characteristic of NbSs interventions. Indeed, the current vision for La Goccia involves the strategic planning and implementation of NbSs, with a foundation in the existing spontaneous ecosystem, which can be identified as a "reclamation forest": an open-air laboratory in which natural reclamation processes coexist with a gradual and limited public use.

Further studies are underway to gather the necessary elements for the development of the reclamation plan and landscape design of the area. Stability and wind resistance of the main tree species in the various soil types are being assessed. The composition of the undergrowth and other microhabitats is being analyzed, and soil microbiology is being monitored and contextualized to the contamination in order to assess the performance of the plant-microorganism system and decide on the types of intervention. Fauna, flora and lichen monitoring will continue, also with experimental studies on bioaccumulation.

The project also aims to underscore the importance of identifying recognized experimental procedures for the implementation of innovative NbSs in urban contexts analogous to La Goccia, leveraging the existing ecosystem in the remediation process.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16091410/s1, Table S1. Number of plants per species and size (Diameter at Breast Height, DBH); Table S2. Number of viable plants per species and size (Diameter at Breast Height, DBH); Table S3. Total number of collected individuals for each taxonomic group, the values of the ecomorphological index (EMI) and QBS-ar in woody (n = 10) and open (n = 6) areas in La Goccia forest; Table S4. Total number of individuals of butterfly species recorded in La Goccia forest (nomenclature follows: [95]); Table S5. Bird species recorded in La Goccia forest, for each species, the total number of individuals, the estimated number of pairs, and the status are reported; Table S6. Mammal species recorded in La Goccia forest, for each species, the status is reported.

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