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Review article

The role of urban forests in tackling air and soil pollution in Italian cities

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ABSTRACT

Urban forests are increasingly recognized as essential components of sustainable city planning, offering multi-functional ecosystem services that address key environmental challenges. This review explores the role of urban vegetation in mitigating air and soil pollution, using Italy as a representative case study. Air pollution - specifically particulate matter (PM), nitrogen dioxide (NO_2), and tropospheric ozone (O_3) - remains a critical health concern in urban areas, while soil contamination by heavy metals and organic pollutants continues to degrade ecosystem functionality. We examined the mechanisms by which urban greenery mitigates these pollutants, focusing on species-specific traits, functional planning, and integrated monitoring strategies. To bridge research and practice, a new strategy for urban greenery planning is proposed, presented here as two case studies. The case first demonstrates an innovative air quality management approach in Florence, combining high-resolution satellite imagery with a new simple biophysical modeling framework (FlorTree model) to evaluate species effectiveness in pollutant removal. The second case synthesizes field-scale phytoremediation projects across Italy, showcasing how selected tree, shrub, and herbaceous species can remediate contaminated urban soils while providing co-benefits such as biomass production and biodiversity support. These findings highlight the global relevance of urban forestry as a low-impact, cost-effective strategy to enhance environmental quality and public health. By integrating green infrastructure into urban policy and land use planning, cities can optimize air and soil remediation, promote ecosystem resilience, and contribute to climate adaptation goals. The review underscores the need for interdisciplinary collaboration, long-term monitoring, and policy alignment to fully harness the potential of urban forests in addressing complex urban pollution dynamics.

1. Introduction

Urban green spaces, which include forests, meadows, residential yards, parks, grassy lawns, engineered green roofs and rain gardens (Paudel and States, 2023), are commonly linked to improvements in air quality, temperature regulation, reduction of the urban heat island effect, increased biodiversity, carbon sequestration, noise reduction, and offer recreational, social, psychological, and aesthetic benefits that enhance urban life and well-being (Hartig et al., 2014; Edeigba et al., 2024). Urban green spaces are also critical to face environmental challenges such as air and soil pollution.

Soil is an integral part of the urban landscape, promoting urban plant nutrition and growth which in turn regulate air quality by intercepting atmospheric particles and adsorbing gaseous pollutants. The presence of

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soil contaminants can affect biogeochemical cycles and plant growth, causing a progressive disruption of ecosystem functioning and services as they are strictly dependent on healthy soil-plant systems (Macci et al., 2025).

Although certain studies warn that the real impact of urban greening on reducing local air pollution might be exaggerated (Pataki et al., 2013; Vos et al., 2013; Yli-Pelkonen et al., 2017a, 2017b), urban green spaces are associated with lowering the population's illness and preventing premature death by improving air quality (Sicard et al., 2025; Kondo et al., 2020). Therefore, policy measures aimed at promoting investment in the green sector are becoming increasingly widespread.

To protect nature and biodiversity, the EU launched the Biodiversity Strategy for 2030 (European Commission, 2020) and requests European municipalities with a minimum of 20,000 inhabitants to develop Urban Greening Plans. With the "With the "Regulation (EU) 2024/1991 (EP, 2024), on nature restoration and amending Regulation (EU) 2022/869" (EP, 2022) aimed to assist the Member States in restoring ecosystems to ensure biodiversity resilience, to contribute to climate change mitigation, For instance, by planting at least 3 billion additional trees by 2030, to guarantee that urban green areas and urban tree canopy cover experience no net reduction in 2030 compared to 2024, and to achieve an increasing trend in the total national area of urban green space by 2031 (European Commission, 2021). These ambitious plans are part of broader efforts to mitigate significant health problems; in 2021, ambient air pollution in the 27 EU Member States was linked to an estimated 253, 000 premature deaths from chronic exposure to $PM_{2.5}$, 52,000 from NO_2, and 22,000 from acute exposure to O_3 (Sicard et al., 2021; European Environment Agency, 2023). However, to address urban environmental challenges such as air pollution and soil degradation, it is essential to improve the functional planning of urban green spaces (Lai et al., 2024).

Italy offers a particularly informative case regarding its urban green spaces, with its mix of historic parks, roadside plantings, and urban forests, that host a wide diversity of plant species, which vary based on geographical location and climate. Native vegetation is often prioritized as it plays a crucial role in supporting regional biodiversity, with the species richness being higher in archaeological sites, open fields, and parks, and the lowest richness observed in residential areas with compact or poor soils (Grapow and Blasi, 1998). However, Italy lacks a unified, up-to-date synthesis that connects national and regional policy instruments with empirical monitoring data. While numerous case reports describe individual greening interventions, no comprehensive review exists that (i) maps policy evolution, (ii) synthesizes empirical evidence on the urban green capacity to reduce air pollutants and improve soil quality, and (iii) illustrates planning tools through novel case studies. Thus, this review aims to provides a comprehensive overview of urban green planning strategies to improve air quality and soil functionality in Italy, delivering an integrated, evidence-based framework for optimizing urban green strategies, and providing lessons transferable to other nations.

1.1. *Literature survey and review*

We conducted a systematic research to synthesize and discuss Italy's use of urban green spaces for improving air and soil quality, focusing on (1) the Italian national and regional policies for enhancing urban air and soil quality through urban greenery, (2) the current status of urban air and soil pollution in Italy, (3) the use of empirical data to quantify the effects of urban green spaces on air and soil improvement, and (4) case studies that demonstrate the success of innovative urban green planning strategies in enhancing air quality and soil functionality.

Regarding air pollution, (1) we identified national and regional policy documents by querying official government repositories, assessing national decrees, and reviewing each Italian region's Air Quality Plans. All texts published were written in Italian; therefore, the document screening was conducted using Italian keywords, such as "qualità dell'aria"; "verde urbano"; "particolato"; "diossido di azoto"; "emissioni VOC"; "ozono". We screened full texts and selected nine documents explicitly motivating urban-green interventions for the mitigation of air pollution. (2) We relied exclusively on the 2023 annual synthesis report published by the National System for Environmental Protection (SNPA) to characterize the current status of urban air pollution in Italy. Next, we discussed these metrics in relation to the new air-quality standards, ensuring a comparison between observed urban air-pollutant levels and evolving regulatory requirements. (3) We systematically searched the database Scopus for peer-reviewed studies published between 2015 and May 2025. The search string combined the concepts of urban green, air pollution, and Italy (TITLE-ABS-KEY), excluding any study carried out in other countries (not Italy). In addition, only studies including empirical or model-based measures of NO_2, PM, or O_3 reduction attributed to urban green were selected. Fifteen publications were selected and the information from each study was discussed. (4) Finally, for the air quality case studies, we reanalyzed two published datasets: the FlorTree model (Manzini et al., 2023), which ranks tree species capacity to remove air pollutants, and a high-resolution satellite mapping approach (Sicard et al., 2023; López et al., 2025), which classifies urban tree species from multispectral imagery, and finally merged both methodologies for presenting a novel tool for urban green planning.

Regarding urban soil contamination the literature review was carried out in March 2025 using the Scopus platform. The search string combined the concepts of phytoremediation and Italy (TITLE-ABS-KEY), excluding any study carried out in other countries. In addition, only the studies carried out at the field scale were considered (i.e., not lab, pot, mesocosm trials). In total, 216 published papers were found. This literature body was reduced by excluding all the documents that were not Research Articles. In addition, a further selection was made by excluding studies that did not report any information about phytoremediation performance in terms of pollutant removal.

2. Policy frameworks and strategies

2.1. *Urban air pollution policy and perspectives from Europe to Italy*

Three national documents from the Ministry of the Environment deserve attention regarding Italy's endorsement of urban greening to improve air quality.

The first is the *"National Urban Green Infrastructure Strategy"* edited by the Ministry of the Environment and Protection of Land and Sea (MATTM, 2018), which provides the guidelines for urban green planning, emphasizing the importance of biodiversity, air quality improvement, and urban livability through expanded greenery. The second is the *"Urban and extra-urban forestation plan"* from the Ministry of Ecological Transition (MTE, 2022b), which highlights the importance of monitoring programs to assess the benefits derived from afforestation, emphasizing the need for both prior and post-evaluations. Although no protocol is provided, the indication for monitoring includes an evaluation along a seven-year monitoring framework with periodic field inspections to verify proper planting and cultivation practices, including irrigation regimes, fertilization, and phytosanitary measures treatments. Additionally, ecological monitoring is recommended to quantify ecosystem services, such as biodiversity enhancement, CO_2 sequestration, pollution removal, and soil quality improvement. The third document was published in 2022 by the Ministry of Ecological Transition as Legislative Decree (DM n.183, 06/08/2022, MTE, 2022a), highlighting the importance of prioritizing plant species that are most effective at absorbing gaseous pollutants and PM in Green Infrastructure (GI) programs.

At the regional level, the decree DM n.183, 06/08/2022, refers to the Regional Air Quality Plan of Tuscany and a web application (https://servizi.toscana.it/RT/statistichedinamiche/piante/) for selecting suitable tree species for GI programs. In fact, Tuscany Region (Central Italy) published in 2018 (Regione Toscana, 2018) the *"Guideline for the*

Selection and Planting of Specific Tree Species for the Absorption of Nitrogen Dioxide, Fine Particulate Matter, and Ozone" which, together with the web application, is an important tool to provide a practical framework for municipalities and individuals to select vegetation that effectively mitigates urban pollution. The guidelines discourage the planting of invasive or poorly adapted species, reflecting a comprehensive commitment to integrating urban greenness into urban planning and utilizing the FlorTree model (Manzini et al., 2023) for ranking tree and shrub species based on their capacity to cope with air pollution.

Still on a regional scale, in northern Italy, the Integrated Regional Air Plan (Emilia-Romagna, 2025) also intends to enhance urban and peri-urban forestry by selecting tree species that cope with air pollutants. The region published the handbook, "*Trees for the City: A Catalogue for Urban Green Infrastructure*" (Regione Emilia-Romagna, 2024), offering a guide to tree and shrub species for planning GI, focusing on climate adaptation and biodiversity, recommending the Tuscany guidelines and the FlorTree model to estimate species-specific absorption of gaseous pollutants and PM retention. Still in Northern Italy, the Green Plan of Padova (Comune-di-Padova, 2022) outlines criteria for planning GI by selecting species that reduce air pollution, such as low-biogenic volatile organic compound (bVOC) emitters, for reducing tropospheric O_3 formation, and evergreen species for improving PM removal. Furthermore, the Regional Air Quality Plan of Piedmont (Regione-Piemonte, 2024) advocates for Nature-based Solutions (NbS) in urban and peri-urban areas to adapt to climate change and enhance ecosystem functionality, focusing on tree species that effectively reduce atmospheric pollutants.

Despite their shared goals of using GI to improve urban air quality, these national and regional instruments are not yet fully harmonized. In practice, municipalities and urban planners must consult multiple, sometimes overlapping guidelines that vary in scope, monitoring requirements, and reporting formats. This fragmentation can hinder the coherent implementation and comparability of data across regions. Establishing a centralized coordination mechanism could close these gaps through initiatives like a unified online platform for uploading monitoring results and standardized reporting templates.

2.2. *Urban soil pollution policy and perspectives from Europe to Italy*

Soil policies aim to protect and enhance soil quality, which directly impacts the growth and sustainability of urban tree populations; hence, soil policies are essential for creating healthy urban environments that can support thriving urban forests. Concerning urban soil policies, the EU "Thematic Strategy on the Urban Environment" (European Commission, 2006) recognizes the importance of soil monitoring as a key indicator determining the quality of urban areas and their capacity to provide ecosystem services. According to the European Environment Agency (2023), 250,000 soils have been identified as contaminated across the EU, mainly by metals and persistent organic pollutants, representing a potential risk to human health and ecological systems. Several other actions to protect soils include the Soil Strategy for 2030, the Biodiversity Strategy for 2030, the Farm to Fork Strategy, the Zero Pollution, the Nature Restoration Law and the European Climate Law (Arias-Navarro et al., 2023).

In Italian environmental legislation, the most common potentially toxic elements (PTE) and organic pollutants are listed in the Legislative Decree (D.lgs.) no. 152/06 "Environmental Regulations". Specifically, this Law defines the procedures, criteria, and methods to be adopted for eliminating, or at least reducing, the contamination source and the concentrations of pollutants in harmony with EU principles and standards. With this aim, the D.lgs. 152/06 reports a table with the soil and subsoil contamination thresholds for 97 parameters, updated by Law no. 116/14 for tin (Sn). The threshold limits are applicable to sites for public, private, and residential green use and sites for commercial and industrial use, representing a fundamental tool for monitoring soil quality and potential environmental health concerns. However, it has been suggested that a proper geochemical survey should consider a much larger number of PTEs, although the current national legislation does not consider them harmful to health (Cicchella et al., 2020). Another critical point concerns the emerging contaminants, which include pharmaceuticals, personal care products, endocrine disruptors, nanomaterials and microplastics (Li et al., 2024). Although these contaminant can pose a great risk for both ecosystems and human health, the development of common detection, monitoring and management strategies, as well as risk assessment models and regulatory frameworks, remains a significant challenge at both EU and National level.

3. Current environmental status in Italy

3.1. *Urban air quality*

The Italian National System for Environmental Protection (SNPA) releases annual reports on air quality throughout Italy. Until the latest report (SNPA – Sistema Nazionale per la Protezione dell'Ambiente., 2024), the exceedances for PM_{10}, NO_2, and O_3 were still based on the limit values specified in Directive (EU) 2008/50/EC (European Parliament and Council, 2008). Thus, they do not consider the World Health Organization Air Quality Guidelines (WHO, 2021 AQGs), which set more stringent targets, or the newly published European air pollution target limit for 2030 (Directive (EU) 2024/2881 of the European Parliament and Council, 2024), which reduces the limits and exceedance days for PM_{10}, NO_2, and O_3 and fills gaps by introducing 24-hour $PM_{2.5}$ limits (Table 1).

In the last SNPA report (SNPA – Sistema Nazionale per la Protezione dell'Ambiente.,2024), the annual PM_{10} limit was not exceeded in Italy, except for one site in Palermo (Sicily – Southern Italy), likely attributable to intense desert sand intrusion events. In contrast, the daily PM_{10} limit was surpassed in 96 stations (17 % of cases). Notably, 80 out of these 96 instances occurred in the Po Valley region (Northern Italy), a hotspot for PM pollution due to its unique meteorological conditions, particularly during winter, which favor the accumulation of atmospheric pollutants and facilitate the chemical-physical processes responsible for secondary pollutant formation. Still, trend analysis over the 2014–2023 decade shows a statistically significant decrease in PM_{10} levels at 53 % of the monitored stations.

Table 1
European current and target limits for air quality for key air pollutants based on the Italian limits (D.Lgs.155/2010), the World Health Organization (WHO) world air quality guidelines and the European Target limit for 2030 (Directive (EU) 2024/2881).

Pollutant	Timing	Italian limits (Directive 2008/50/EC)	WHO air quality guidelines	European Target limit for 2030 (Directive 2024/2881)
PM_{10}	24 h	50 μg/m^3, ≤ 35 exceedances/yr	45 μg/m^3*	45 μg/m^3 ≤ 18 exceedances/yr
	Calendar year	40 μg/m^3	15 μg/m^3	20 μg/m^3
$PM_{2.5}$	24 h	-	15 μg/m^3*	25 μg/m^3 ≤ 18 exceedances/yr
	Calendar year	25 μg/m^3	5 μg/m^3	10 μg/m^3
NO_2	24 h	200 μg/m^3, ≤ 18 exceedances/yr	25 μg/m^3*	200 μg/m^3 ≤ 3 exceedances/yr
	Calendar year	40 μg/m^3	10 μg/m^3	20 μg/m^3
O_3	MDA8**	120 μg/m^3 ≤ 25 exceedances/yr	100 μg/m^3*	100 μg/m^3 ≤ 3 exceedances/yr (2050 target)
	AOT40 (May to July) for the protection of vegetation	18 000 μg/m^3 × h (3 yr avg)	-	6 000 μg/m^3 × h (3 yr avg)

* 99th percentile (i.e., 3–4 exceedance days per year)
** Mean daily average

For NO_2, the hourly limit is not exceeded across all Italian monitoring stations. Also, the annual limit is largely respected nationwide, with 98 % in compliance. All exceedances were recorded at stations across Italy influenced by high traffic volumes in major urban areas such as Turin (Piedmont – Northern Italy), the Milan metropolitan area (Lombardy – Northern Italy), Genoa (Liguria – Northern Italy), Rome (Lazio – Central Italy), Naples (Campania – Southern Italy), Catania and Palermo (Sicily – Southern Italy). Over the decade from 2014 to 2023, a statistically significant declining trend in NO_2 levels was identified in 85 % of the monitoring stations (SNPA – Sistema Nazionale per la Protezione dell'Ambiente.,2024).

The situation is different for O_3. In 2024, the health protection limit was exceeded for more than 25 days in 43 % of the stations, particularly in the Po Valley regions (Northern Italy) and at some high-altitude sites. The highest O_3 concentrations were observed in suburban and rural areas downwind of highly urbanized regions. Statistical analysis for 2014–2023 indicates that a trend in the O_3 levels is not evident across most monitoring stations. Despite a significant decline in peak O_3 levels over time, O_3 exceedances in Italy frequently occur at higher levels than those in other European countries, especially in urban areas (Paoletti, 2006).

Italy's current status regarding air pollution limit exceedances might change when the new criteria Directive (EU) 2024/2881 is implemented. To achieve the 2030 target, the Italian Ministry of the Environment and Energy Security published the National Program for the Control of Air Pollution (Programma nazionale di controllo dell'inquinamento atmosferico PNCIA.,2021) with the aim to guide a reduction of 40 % in $PM_{2.5}$, 65 % in NO_x and 46 % in non-methane VOCs (key O_3 precursors) relative to 2005 levels. In detail, to reduce emissions from residential biomass combustion, which cause winter peaks in PM, the PNCIA recommends replacing old wood-burning stoves with certified high-efficiency devices, while to reduce emissions from road transport, it aims to accelerate the transition to electric vehicles by investing in public transport and cycling infrastructure in urban areas.

3.2. Urban soil quality

Several studies assessed soil pollution in Italian cities, revealing that urban soils are potential sinks for PTEs and organic contaminants (polycyclic aromatic hydrocarbons, PAHs; polychlorinated biphenyls, PCBs; polychlorinated dibenzo-p-dioxins, PCDD; dibenzofurans, DFs; polychlorinated naphthalenes, PCNs; and organochlorine pesticides, OCP).

Among PTEs, chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) have been commonly found in urban soils of major urban areas in Northern Italy (Biasioli and Ajmone-Marsan, 2007; Fabietti et al., 2010; Sialelli et al., 2011). Diana et al. (2022) identified urban activities and soil/road dust resuspension as the main sources of metals in a northern area at the border of the Po Valley region (Northern Italy), which represents one of the most polluted areas of Europe. Still in northern Italy, in Turin, the finer soil particles showed metal enrichment of Cu, Zn, and, to a lesser extent, Pb, suggesting that metal availability was higher in the clay fraction than in other fractions, highlighting that the overall soil concentration cannot serve as a reliable general indicator of metal bioaccessibility in urban soils (Madrid et al., 2008).

Concentrations and bioaccessibility of soil metals in Turin (Northern Italy) were higher in roadside soils than in soils from parks, and among soil metals, Pb and Zn bioaccessibilities were found to be higher in the stomach, while Cr was more bioaccessible in the intestine (Sialelli et al., 2011). Moreover, Ajmone-Marsan et al. (2019) demonstrated that the release of Cu, Pb, and Zn can be enhanced by waterlogging due to extreme rainy events, suggesting that the submersion of contaminated soils may lead to serious environmental risks in urban areas context. To evaluate the remediation potential of plant species in Turin urban soils, Gaggero et al. (2020) investigated the concentrations of 22 PTE in both city central and peripheral urban parks of Turin and evaluated the efficiency of four different plant species (*Brassica juncea*, *Helianthus annuus*, *Zea mays* and *Pteris vittata*) for phytoremediation purposes, highlighting a species-specific uptake ability depending on the considered PTE.

Concentrations of organic pollutants, such as PAHs, PCBs, PCDD, and DFs, were often above national legislation limits in urban soils of the parks of Turin (Northern Italy, Biasioli and Ajmone-Marsan, 2007), especially in historical parks, indicating that soil age could play a major role in determining the soil contamination level. Fabietti et al. (2010) found an enrichment of some contaminants such as metals, PCBs, and PAHs in the urban environment in Piedmont (Northern Italy) with respect to their surrounding natural and agricultural areas, while other contaminants such as PCDD and DFs showed lower differences, confirming their widespread and ubiquitous pollution.

Furthermore, significant increases of some PTE (e.g., Cu, Pb, Zn) were observed in the topsoil of Ravenna urban park (Emilia-Romagna – Northern Italy), where their concentrations often exceeded the threshold values established by Italian law (D.lgs 152/2006).

A preliminary review in Central-South Italy showed that OCP residues in soils ranged from not detected (n.d.) to 1043 ng g^{-1} (with a mean of 29.91 ng g^{-1}) and from n.d. to 1914 g^{-1} (with a mean of 60.16 ng g^{-1}) in urban and rural area, respectively (Thiombane et al., 2018).

Recently, the quality of 31 urban soils in Central Italy (Tuscany) was determined by analyzing total petroleum hydrocarbons (TPHs) and several PTE such as Cr, Cu, Ni, Pb, Zn, cadmium (Cd), mercury (Hg), manganese (Mn), and the platinum (Pt) group elements (Cardelli et al., 2017). Results indicated a widespread soil pollution, with almost all the monitored sites exceeding the legal limit of 60 mg kg^{-1} for TPHs in residential areas, while the geological accumulation index (Igeo) indicated no Cd, Cu, Mn, Ni, and Zn pollution and minimal Pb and Cr pollution due to anthropogenic enrichment. Legal Hg and Zn limits of 1 and 150 mg kg^{-1}, respectively, were exceeded in about 20 % of the monitored sites, while the limits for Cd (2 mg kg^{-1}), Cr (150 mg kg^{-1}), and Cu (120 mg kg^{-1}) were exceeded in only one site. The concentration of Hg ranged between 0.04 and 9.61 mg kg^{-1}, with two sites exceeding the more restrictive legal limit of 5 mg kg^{-1} for industrial areas, while the Ni legal limit of 120 mg kg^{-1} was never exceeded. Coastal areas in Tuscany (Central Italy) have also shown metal contamination, with Pb and Cu reaching the highest levels in roadside soils and in areas with past agricultural activities like vineyards, respectively (Bretzel and Calderisi, 2006). Regarding chemical alterations, Italian urban soils are generally characterized by an alkaline pH due to the presence of a high content of calcium carbonate from construction debris and release of calcareous solution (Ungaro et al., 2022), which can affect the bioavailability of nutrients and heavy metals altering their uptake by urban trees growing in a Tuscany park (Scartazza et al., 2025).

The Hg concentrations of urban soils in Central Italy (Tuscany) were aligned with those found in other cities of Central and Southern Italy, such as Rome (0.17–1.48 mg kg^{-1}; Cenci et al., 2008), Naples, Benevento, Caserta, Salerno, and Avellino (0.01–2.66 mg kg^{-1}; Cicchella et al., 2008). Soils of school gardens, public parks, sport grounds and roadsides were analysed also in Serchio River Valley (Tuscany – Central Italy), indicating that Cu, Zn, and Cd represent the main contaminants in surface soil, likely originated by deposition of airborne particulate matter from metallurgical activity (Petrini et al., 2022). Furthermore, the veichle traffic contributed significantly to metal pollution in city soils of Rome (Lazio, Central Italy), especially Pb, Cu, Ni and Zn.

Cicchella et al. (2003) analyzed the Pt and palladium (Pd) soil concentrations in Naples metropolitan area (Central Italy), reporting anomalous values for Pt (> 6 mg kg^{-1}) and Pd (> 17 mg kg^{-1}) and a positive correlation between these element concentrations with road distribution and major traffic flow, possibly due to catalytic converter attrition. In the same metropolitan area, Giaccio et al. (2012) analyzed the geochemical distribution of soil heavy metals, and found a strong correlation between anomalous Pb and antimony (Sb) concentrations and men with poor semen quality, while other elements showed a weaker correlation (Hg and Zn) or the absence of significant correlations.

A geochemical survey was conducted in the Salerno urban area (Campania – Southern Italy) to determine the source patterns of major, minor, trace, and ultra-trace elements in 151 urban topsoils (Cicchella et al., 2020). The results highlighted that while the distribution of major and minor elements was independent of human activities, many trace and ultratrace elements were mainly located in highly populated areas characterized by industry activities and heavy road traffic, supporting their anthropogenic source. Among these elements, some PTE (e.g., Pb and Zn) showed concentrations that reached values tens of times higher than the legal limits, causing potential health problems. Papa et al. (2012) determined the concentrations of V, Cd, Cr, Pb, Ni, Cu, and PAHs in *Quercus ilex* L. leaves in the city of Caserta (Campania – Southern Italy) demonstrating that this species represented a useful bioindicator of urban pollution and a good candidate for phytoremediation purposes.

Other studies conducted in Southern Italy analyzed the spatial distribution of soil Pb concentration in urban and peri-urban soils collected along 149 locations (Calabria, Southern Italy) to assess the probability of exceeding the critical threshold for health risks (Guagliardi et al., 2015), showing that large polluted areas exceeded the Italian regulatory values. To evaluate the plant phytoremediation potential in the Calabria region, Perri et al. (2024) analyzed the concentration of Zn, Cd, Co and As in black poplar leaves and soil samples from three urbanized sites showing that these elements exceeded reference values for unpolluted sites, indicating potential environmental risk. These authors demonstrated that black poplar trees were able to reduce the extent of the contamination by highly frequent toxic pollutants in urban areas representing a valuable NbS for monitoring and restoration in urban context.

Furthermore, studies carried out in the insular Italian regions reported the concentrations of Mn, Cd, Zn, Ni, Cr, Cu, Pb, Hg, Sb, vanadium (V), and cobalt (Co) on 70 topsoil samples collected from green areas and parks in the city of Palermo (Sicily – Southern Italian), showing median values of Pb, Zn, Cu, and Hg concentrations of 202, 138, 63, and 0.68 mg kg^{-1} respectively, much higher than uncontaminated Sicilian soils (Manta et al., 2002). Regarding organic pollutants, De Guidi et al. (2017) investigated the urban soil contamination with PAHs and nitro-PAHs in the city of Catania (Sicily – Southern Italy). These authors suggested a strong contribution from incomplete combustion of gasoline or other fuels also due to the vicinity to the airport and demonstrated the effectiveness of microwave heating as remediation treatment for contaminant removals.

Most of the above-mentioned studies have been conducted in the main urban areas of the Northern (Piedmont, Emilia-Romagna), Central (Tuscany, Lazio) and Southern (Campania, Calabria, Sicily) Italian regions. However, further studies are needed to broaden the geographical coverage and temporal trend at the national scale, especially in the highly urbanized regions of Northern Italy, such as Lombardy, where cultivated soils south of Milan and other urban areas of Lombardy were found highly enriched in metals such as Cd, Cu, Pb and Zn (Sacchi et al., 2020). Furthermore, more studies are needed to evaluate emerging contaminants such as pharmaceuticals that may pose serious risks to ecosystems and human health (Li et al., 2024). Indeed, only a few studies have analyzed the fate of emerging contaminants in Italian soils and they are generally related to agricultural soils, as in the case of durum wheat grown on irrigated land with treated wastewater in Southern Italy (Basilicata region, Denora et al., 2024), but a gap remains to be filled regarding urban soils. Finally, the combination of soil and vegetation contaminant analyses in urban environments could provide fundamental information to evaluate the most suitable plant species to be used as bioindicators of soil contamination and as NbS tools in remediation strategies based on urban forestry plans.

4. Impact of urban green spaces

4.1. Contributions to air quality improvement

Several studies have focused on the contribution of urban green spaces to improving air quality in Italy. The methodologies include direct measurements of pollutant removal by specific plant species and modeling approaches to estimate pollution reduction attributed to urban greenery. Table 2 synthesizes 15 scientific studies conducted in Italy from 2015 to 2024 that examine the role of urban green spaces in enhancing air quality.

Urban vegetation ability to reduce air pollution varies by species and environmental conditions (Manzini et al., 2023). Indeed, PM and NO_2 concentrations are often associated with vehicle traffic and emissions from heating systems, typically peaking in winter (Tammekivi et al., 2023), while O_3 is a pollutant linked to summer weather, as it is a secondary pollutant generated in the presence of bVOC and solar radiation (Zhao et al., 2018).

Species-specific differences in pollutant removal capacity are influenced by morphological leaf traits and their habit (Grote et al., 2016). Usually, species with smaller and complex-shaped leaves with higher surface roughness are associated with better PM retention (Moura et al., 2024). For instance, the assessment of 22 plant species located in different urban zones in the city of Lucca (Tuscany – Central Italy) highlighted the influence of environmental conditions and species-specific traits in their PM accumulation capacities. The study revealed that evergreen species consistently captured higher PM levels, especially in urban traffic zones where pollution concentrations are higher. In this case, particular attention must be given to the broadleaf evergreen species *Quercus ilex* L., which was revealed as an efficient species to capture both fine ($PM_{2.5}$) and larger particles (PM_{10}) in studies conducted in different cities of Italy such as Terni (Umbria – Central Italy; Sgrigna et al., 2015), Naples (Esposito et al., 2020), Rimini (Emilia-Romagna – Central Italy; Vigevani et al., 2022), and Perugia (Umbria – Central Italy; Orlandi et al., 2022), with PM accumulation capacity positively correlated to leaf traits (leaf length, width, circularity, and dry matter content; Esposito et al., 2020). Regarding the shrubs, two species, i.e., *Viburnum lucidum* L. and *Photinia* × *fraseri* cv. Red Robin Dress, used as a roadside vegetation barrier in Pescia (Tuscany – Central Italy), was demonstrated to steadily change the dynamics of PM deposition with a reduction of about 30 % (Mori et al., 2018).

Simulation models assess the local-scale benefits of urban treescapes, focusing on quantifying the capacity of urban forests to intercept PM. Studies conducted in the Metropolitan city of Naples (Campania – Southern Italy; Sebastiani et al., 2021) and the city of Ferrara (Emilia-Romagna – Central Italy; Muresan et al., 2022) underscored that the total PM_{10} removal efficiency is higher for conifers than broadleaves, with a peak deposition rate during winter. These findings are in agreement with the PM_{10} dry deposition simulated by the model AIRTREE for two representative Italian urban parks located in Rome (Lazio – Central Italy) and Turin (Piedmont – Northern Italy) (Fares et al., 2020).

In contrast, modeled PM_{10} removal in three Italian coastal cities—Genoa (Liguria – Northern Italy), Bari (Apulia – Southern Italy), and Reggio Calabria (Calabria – Southern Italy)—was reported to be more efficient in evergreen broadleaves than in deciduous and conifer species (Nardella et al., 2023). Focusing on the metropolitan city of Rome (Lazio – Central Italy), another study also described evergreen species exhibiting higher PM_{10} removal efficiency per hectare than deciduous species (+ 15–22 %, Marando et al., 2016).

Regardless of the study, urban trees effectively reduce PM in the air. Simulations estimate a contribution to PM removal of about 4 tons of PM_{10} within one year in an urban park in Rome (Lazio – Central Italy; Silli et al., 2015). Similarly, research on the entire urban forest of Florence (Tuscany – Central Italy) estimated a significant PM_{10} removal of 171.3 t/year (Bottalico et al., 2017).

Urban vegetation can also absorb gaseous pollutants like O_3 and

Table 2
Comparison of urban vegetation role in air pollution mitigation and policy implications across Italian cities.

Species Studied	Italian City/ Region	Target Pollutants	Key Findings	Public Policy Implications	Reference
Evergreen/ deciduous broadleaves and conifers	Rome/Lazio	PM_{10}	Trees, especially evergreen broadleaves, effectively reduce PM_{10} concentrations.	Emphasize the role of green infrastructures in urban forests for improving air quality.	Silli et al., 2015
Evergreen/ deciduous broadleaves and conifers	Rome/Lazio	PM_{10}	Deciduous broadleaves represent the most abundant tree functional group and yield the highest total annual PM_{10} deposition values but the removal efficiency is higher in evergreen than in deciduous species.	Support to the crucial role played by nature-based solutions for human well-being in urban areas. The monetary evaluation indicated that the overall PM_{10} removal value amounted to 161.78 million euros.	Marando et al., 2016
General tree species	Perugia/Umbria	PM_{10}	High PM_{10} capture by specific tree species contributes to air purification.	Encourages integration of effective species in urban planning for air quality.	Orlandi et al., 2022
Evergreen/ deciduous broadleaves and conifers	Naples/Campania	PM_{10}	1148.30 Mg of PM_{10} are annually removed by Urban Green infrastructure. The removal efficiency largely varies across seasons and different vegetation functional groups.	The removal rate was calculated as equal to 36 million euros/year.	Sebastiani et al., 2021
Evergreen/ deciduous broadleaves and conifers	Genoa/Liguria, Bari/Puglia and Reggio Calabria/ Calabria	PM_{10}	The highest annual average PM_{10} removal efficiencies is exhibited by evergreen broadleaves. Deciduous broadleaves also display high efficiency values, despite a marked seasonality caused by leaf abscission.	Support for sustainable planning and management of UGIs. Maintaining a functionally-mixed species composition in the UGIs is desirable for guaranteeing the continuous removal of PM_{10} throughout the year.	Nardella et al., 2023
Quercus ilex	Terni/Umbria	PM	Urban *Quercus ilex* trees can remove PM from the air, with differential deposition linked to traffic roads.	Inform urban green management and policies regarding the UGIs capacity for air pollution mitigation.	Sgrigna et al., 2015
Photinia x *fraseri*; *Viburnum lucidum*	Pescia/Tuscany	PM	Evergreen shrubs can be effectively used as vegetation barrier to remove PM.	Provide insights into the composition of new road UGIs to improve air quality.	Mori et al., 2018
Various tree species	Rimini/Emilia-Romagna	PM	*Quercus ilex* accumulated more PM than the other studied species	The findings are useful to UGI design, considering people's health and sustainable cities.	Vigevani et al., 2022
Various tree species	Lucca/Tuscany	PM	Mitigate PM capacity is not uniform across species or seasons.	Importance of selecting species with specific traits that enhance air pollution mitigation.	Moura et al., 2024
Evergreen/ deciduous broadleaves and conifers	Rome/Lazio	O_3, PM_{10}	Evergreen species displayed higher PM_{10} removal efficiency, whereas deciduous species showed higher O_3 absorption.	Spatially explicit evidence may assist policymakers in land-oriented decisions toward improving UGI and maximizing ES.	Fusaro et al., 2017
Urban forests	Florence/Tuscany	O_3, PM_{10}	Urban forests in Florence remove significant amounts of O_3 and PM_{10}.	Highlights the role of urban forests in air quality improvement strategies.	Bottalico et al., 2017
Urban parks	Rome/Lazio and Turin/Piemont	O_3, PM	Total annual removal (kg/ha) of 1005 and 500 kg of CO_2, 8.1 and 1.42 kg of O_3, and 8.4 and 8 kg of PM_{10}. Differences in pollutant sequestration between urban areas and among species.	Urban parks represent a moderate sink of pollutants.	Fares et al., 2020
Evergreen/ deciduous broadleaves and conifers	Ferrara/Emilia-Romagna	O_3, PM_{10}	The Urban Green Infrastructure removed about 19.8 Mg of PM_{10} and 8.6 Mg of O_3.	The findings meet with the EU Biodiversity strategy for 2030	Muresan et al., 2022
Various tree species	Milan/Lombardia and Bologna/ Emilia-Romagna	O_3, NO_2 and PM	Deciduous broadleaves and evergreen conifers effectively remove air pollutants.	Supports species selection in urban greening for maximum ecosystem services.	Zappitelli et al., 2023
Urban trees and green infrastructure	Bolzano/Trentino-Alto Adige	O_3, NO_2	Urban trees remove significant amounts of air pollutants and reduce temperatures.	Inform urban planning for air quality improvement and urban heat island mitigation.	Russo et al., 2016

NO_2, depending on the plant's eco-physiological traits, particularly the stomatal conductance (g_s), as higher g_s promotes increased air pollution uptake (Manzini et al., 2024). In fact, in the cities of Milan (Lombardy – Northern Italy) and Bologna (Emilia-Romagna – Central Italy), the significant presence of deciduous broadleaves in urban greening was particularly effective in removing NO_2 and O_3 (Zappitelli et al., 2023). While the urban forests in Florence (Tuscany – Central Italy) can remove 77.9 tons of O_3 annually (Bottalico et al., 2017), the total estimated air pollution removal by trees in Bolzano (Trentino-Alto Adige – Northern Italy) was 2.42 tons per year, with O_3 being the most prominent air pollutant removed (Russo et al., 2016).

Evidence for the air pollution removal potential of urban greenery remains optimistic yet highly uncertain, especially regarding species traits, local emission patterns, and seasonal meteorology, as well as how vegetation is defined and inventoried. Furthermore, assumptions necessary for conducting scientific studies, such as neglecting particle resuspension, wintertime physiological down-regulation, species heterogeneity, canopy porosity, or wet scavenging, may induce errors, and consequently, estimations are prone to over- or under-estimates. Furthermore, species-specific O_3-forming potential (OFP) can enhance O_3 and secondary aerosol formation, turning a potential service into an ecosystem disservice. Such features are mostly not considered in the presented studies; however, evidence of remarkable bVOC emission in ornamental species implies an OFP far higher than the O_3 removal capacity (Manzini et al., 2024).

Future work should couple dynamic vegetation features and atmospheric chemistry models, integrating species-specific traits, seasonal stomatal uptake features, and BVOC emissions rates, together with high-resolution seasonal urban green inventory maps, and a continuous and extensive monitoring station network, to provide empirical long-term monitoring data and ensure comparable national and regional studies with reduced bias.

4.2. Contributions to soil quality improvement

Several research projects were carried out in Italy on the effect of urban vegetation on soil quality (Table 3). Some were dedicated to specific soil traits. For instance, a recent study carried out in Milan (Northern Italy) aimed at evaluating the soil organic matter (SOC) stock in the topsoil for different urban land uses (i.e., parks and non-parks) and land covers (i.e., wooded and grassland areas), revealed higher SOC concentration in vegetated urban parks (7.9 ± 2.4 kg m^{-2}) compared to other land cover types (unvegetated) (5.3 ± 2.5 kg m^{-2}), with SOC stock values comparable with forests, pastures, and grasslands of the same region and higher than in croplands (Canedoli et al., 2020). These results have two important consequences: vegetation in urban spaces enhances the organic matter content in the soil and may function as a carbon sink, as also observed by other scientists (Setälä et al., 2016). The soil organic carbon stock in urban green spaces is known to be in general lower than in natural habitats (Lindén et al., 2020). However, the amount of SOC accumulated by urban vegetation depends on many other variables including species composition, with conifers normally accumulating more SOC than broadleaves (Xu et al., 2021), vegetation structure, mixed tree-shrub dominated stand showed higher SOC concentration than to single tree or shrub dominated stand (Parvin et al., 2025) and anthropogenic effects, management regimes such as adding organic amendments are assumed to increase C accumulation in urban soils (Bae and Ryu, 2015). Other studies focused on the role of green spaces in affecting the microbial composition of the soil. Recent studies utilizing DNA metabarcoding techniques and GC-MS analysis assessed the soil quality of urban flowerbeds in Prato (Tuscany – Central Italy). This research focused on microbial biodiversity and the profiles of volatile organic compound (VOC) emissions, aimed at assessing the correlation between the composition of the microbial community and the patterns of soil VOCs (Sillo et al., 2024). The primary conclusions indicated that tree species found in urban environments significantly influenced soil microbial communities and might have facilitated the recruitment of particular microbial taxa, for instance, fungi from the *Pseudeurotium* genus and bacteria such as *Paenarthrobacter* and *Pseudomonas,* which can break down specific classes of VOCs. Other scientists were working more on the soil biological quality of urban parks, highlighting the presence of green spaces along with maintaining a canopy cover and a litter layer as crucial factors favouring high soil diversity of specific animal groups, such as Collembola (Milano et al., 2017).

Other studies investigated soil fertility as a whole. The use of increasing amounts of composted sewage sludge as an amendment was evaluated on the soil chemical and physical characteristics of three native Mediterranean woody hedge species (i.e., *Rhamnus alaternus* L., *Phillyrea angustifolia* L., and *Myrtus communis* subsp. Tarentina L.) in Bari (Southern Italy). Soil physical characteristics were positively influenced by the addition of sewage sludge with the high supply rate (i.e., 45 %), showing an increase in both moisture and infiltration values, thereby increasing the amount of water available for the plant in the soil (De Lucia et al., 2013).

Another similar study on the effects of compost supply on urban Technosol in Naples (Southern Italy) used an herbaceous spontaneous species, *Malva sylvestris* L., and Mediterranean sclerophyllous woody plants, *Phillyrea angustifolia* L., and *Quercus ilex* L. The authors found that compost enrichment resulted in higher nutrient availability and C/N ratio over time. However, the beneficial effects on plant physiology and productivity were significant only for the colonizing and fast-growing herbaceous *M. sylvestris* but not for sclerophyllous species, which likely require a longer period to provide positive responses (Vitale et al., 2024).

A more ecologically oriented study, aimed at evaluating ecosystem services and possible synergies and trade-offs between different soil properties, was carried out in Carpi (Northern East Italy) (Ungaro et al., 2022). In this case, biological fertility, potential habitat for organisms, water regulation and storage, soil buffering capacity, and carbon stock were assessed in 9 urban green areas. Soil organic carbon content was, on average, higher in urban green areas than in agricultural soils. In

Table 3
Research projects carried out in Italy related to the role of urban greening and soil quality.

Systems Studied	Italian City/ Region	Target Soil	Key Findings	Public Policy Implications	Reference
Different urban land uses (park/ non-park) and covers (woodland/grassland)	Milan/ Lombardy	soil organic matter (SOC) stock in the topsoil	Average SOC of urban parks was higher than urban non-parks; Urban parks showed SOC stock values comparable with forests, pastures and grasslands and higher than croplands	Emphasize the role of vegetation in the formation of stable soil carbon stock	Canedoli et al., 2020
Q. ilex, *Tilia* spp., *Q. robur* in urban park vs. flowbeds	Prato/ Tuscany	Microbial communities	Tree species present in urban areas had a significant impact on soil microbial communities	The choice of tree species may contribute to recruit specific microbial taxa for degradation of some soil pollutants	Sillo et al., 2024
Urban parks; Roadside green and Agricultural fields	Carpi/ Emilia Romagna	Biological fertility, potential habitat for organisms, water regulation and storage, soil buffering capacity and carbon stock	Soil disturbance and vegetation cover density affect soil functions	Soils in urban areas may provide the same level of biological quality as agricultural or forest soils	Ungaro et al., 2022
Xerogardening native shrub species (*Rhamnus alaternus*, *Phillyrea angustifolia*, and *Myrtus communis* subsp. Tarentina) subjected to amendment with sewage sludge	Bari/Apulia	Physical (Colour, Moisture) and chemical (Electrical conductivity, Total organic matter, pH, Total nitrogen, P, Macronutrient and heavy metals)	Positive effect of sewage sludge application on soil characteristics	Hedge establishment based on the use of composted sludge is feasible and helpful to mitigate the environmental impact of organic waste disposal	De Lucia et al., 2013
Soil properties along the urbanization gradient on a vegetation dominated by *Quercus ilex*	Pisa, Livorno/ Tuscany	NO_2 emissions, pH, EC, TOC, and TN $\delta^{13}C$ and $\delta^{15}N$ in soil and plant litter, and enzymatic activities	Enhanced N cycles and SOC degradation rates in urban and peri-urban sites compared to natural sites	Vegetated semi-natural and natural areas can attenuate soil carbon losses	Vannucchi et al., 2025
Technosol with *Malva sylvestris* and Mediterranean sclerophyllous woody plants *Phillyrea angustifolia*, and *Quercus ilex*	Naples/ Campania	pH, soil water content (SWC), total carbon (Cs), nitrogen (Ns), and their ratio (C/Ns), soluble carbon (Sol Cs), nitrogen (Sol Ns), and their ratio (Sol C/Ns)	Higher nutrient availability and C/N ratio over time. Positive effect on plant physiology only for *M. sylvestris*	Compost is very suitable for ameliorating the quality of Technosols in urban greening	Vitale et al., 2024

addition, vegetated urban soil showed a decrease in runoff coefficient of the built-up environment compared to vegetation, highlighting the relevance of protecting areas of unsealed urban soils that can positively contribute to the management of urban storm waters. Also the main indexes for soil Biological Fertility and Biological Quality was higher in vegetated urban areas compared to the other green types, supporting the idea that natural conditions and sustainable soil management can support soil health in urban area while, disturbance factors such as traffic, compaction, or frequent interventions can negatively affect soil health. The study also showed that urban parks act as a biodiversity pool in urban areas, suggesting that the soils of urban green areas may provide the same level of biological quality as natural soils.

The change in soil functional properties and traits (i.e., NO_2 emissions, pH, EC, TOC, TN, enzymatic activities, $\delta^{13}C$, and $\delta^{15}N$ in soil and plant litter), along an urbanization gradient was assessed in three sites with different degrees of urbanization (i.e., natural, peri-urban, and urban), dominated by *Quercus ilex* L., around two towns (i.e., Pisa and Livorno in Central Italy). Results showed more rapid N cycles and organic matter degradation rates, as well as nitrification and denitrification in urban and peri-urban sites as opposed to natural sites, thereby highlighting the important contribution of vegetated semi-natural areas to attenuate soil carbon losses (Vannucchi et al., 2025).

Overall, most of these studies highlight that urban vegetation in Italy, in particular urban forests, may significantly promote specific ecosystem services related to soil, including regulating services (such as carbon sequestration) and supporting services (such as soil formation and habitats for wildlife). This is in line with recent studies that report urban greenspaces and nearby natural areas support similar levels of soil ecosystem services. In fact, recent findings show that urban greenspaces are more similar to natural environments than previously thought (Eldridge et al., 2024). This highlights the importance of managing urban greenspaces for both supporting multiple ecosystem services and their social and recreational value.

5. Case studies

This section presents two complementary case studies illustrating the effectiveness of urban vegetation in pollution control across different environmental compartments. Section 5.1 is a novel integrative study conducted in Florence (Central Italy) that evaluates urban greenery capacity to reduce atmospheric concentrations of O_3, NO_2, and PM_{10}. Section 5.2 synthesizes multiple applied studies carried out across Italy, focusing on the use of plant species for phytoremediation of contaminated urban soils. Together, these case studies underscore the multifaceted role of vegetation in improving urban environments.

5.1. Effectiveness in applying innovative urban planning strategies to improve air quality: Florence case study

A new strategy for urban greenery planning is proposed here, which unifies two recently developed innovative methodologies. The first one is the FlorTree model (Manzini et al., 2023), a species-specific approach

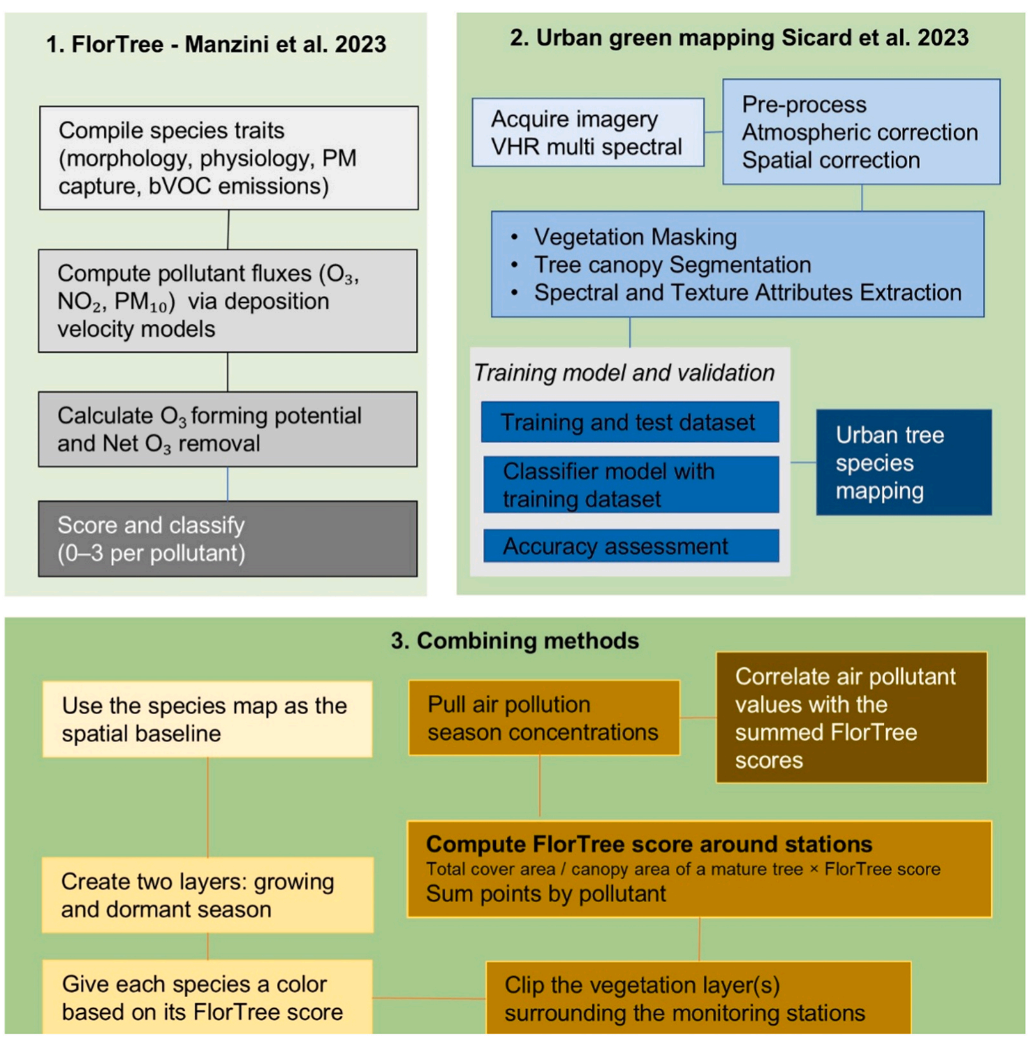

Fig. 1. Flowchart of the methodology used for Florence case study.

that focuses on multiple parameters, such as maximum g_s, bVOC emissions, and leaf trait-based deposition velocity, to classify the air pollution removal capacity of hundreds of plant species. The second is the urban green mapping method, published by Sicard et al. (2023) and Lopez et al. (2025), which is an efficient satellite-based approach using high spectral and spatial resolution satellite imagery to identify plant species within urban contexts (accuracy rate of 83 %). For the case study presented in this publication, both methods were combined to verify urban greenery' potential to cope with the target air pollutants O_3, NO_2, and PM_{10} in the urban area of Florence (Central Italy). The flowchart of the procedure is shown in Fig. 1.

Initially, the distribution of tree species identified in the city of Florence (Fig. 2) enabled the classification of the tree species based on the scores suggested by FlorTree. According to the model, a score of 0, 1, 2, or 3 was assigned to each species to rank its capability to remove O_3, NO_2, and PM_{10}. The classification was done using the QGIS software for both the growing (Fig. 2A) and the dormant (Fig. 2B) seasons, as for the dormant season, the deciduous species were removed from the scoring.

Air quality monitoring data from stations in Florence belonging to the Regional Agency for Environmental Protection of Tuscany (ARPAT) and the environmental monitoring stations (MS) from the Airqino platform (https://www.airqino.it/en/) were selected. The average hourly concentrations of O_3 (Fig. 3C and G) and NO_2 (Fig. 4C and G), along with the daily average concentration of PM_{10} (Fig. 5C and G) during the growing and dormant seasons of 2022, were chosen to investigate the correlation between pollutant levels and the FlorTree score, taking into account various distances from the monitoring stations.

As a common spatial scale employed in air pollution dispersion models is the microscale (i.e., 10–500 m, Tiwari et al., 2019), circular buffer zones surrounding the air pollution stations in both climatic seasons (growing and dormant) we chosen to categorized spatial scales (Venter et al., 2024) of street-level (50 m) and different borough-levels (100, 200, and 500 m).

The total coverage area corresponding to each species was calculated. The total coverage area was divided by the canopy area of a mature tree for each species e.g., if the total coverage area of a species is 100 m^2, and an adult mature tree has a 10 m^2 canopy area, then, if the FlorTree score is 3 for this species, this area will compute 30 points, even if composed of more or fewer than 3 individuals. The total FlorTree score surrounding the monitoring station was computed for the target air pollutants O_3 (Fig. 3B and F), NO_2 (Fig. 4B and F), and PM_{10} (Fig. 5B and F).

Correlations between pollutant concentrations and FlorTree scores were tested with Pearson's correlation coefficient; associations with $p > 0.05$ were considered not significant, and no additional covariates or transformations were applied. Temporal and spatial variability were handled by using only complete, gap free series (no gap filling) restricted

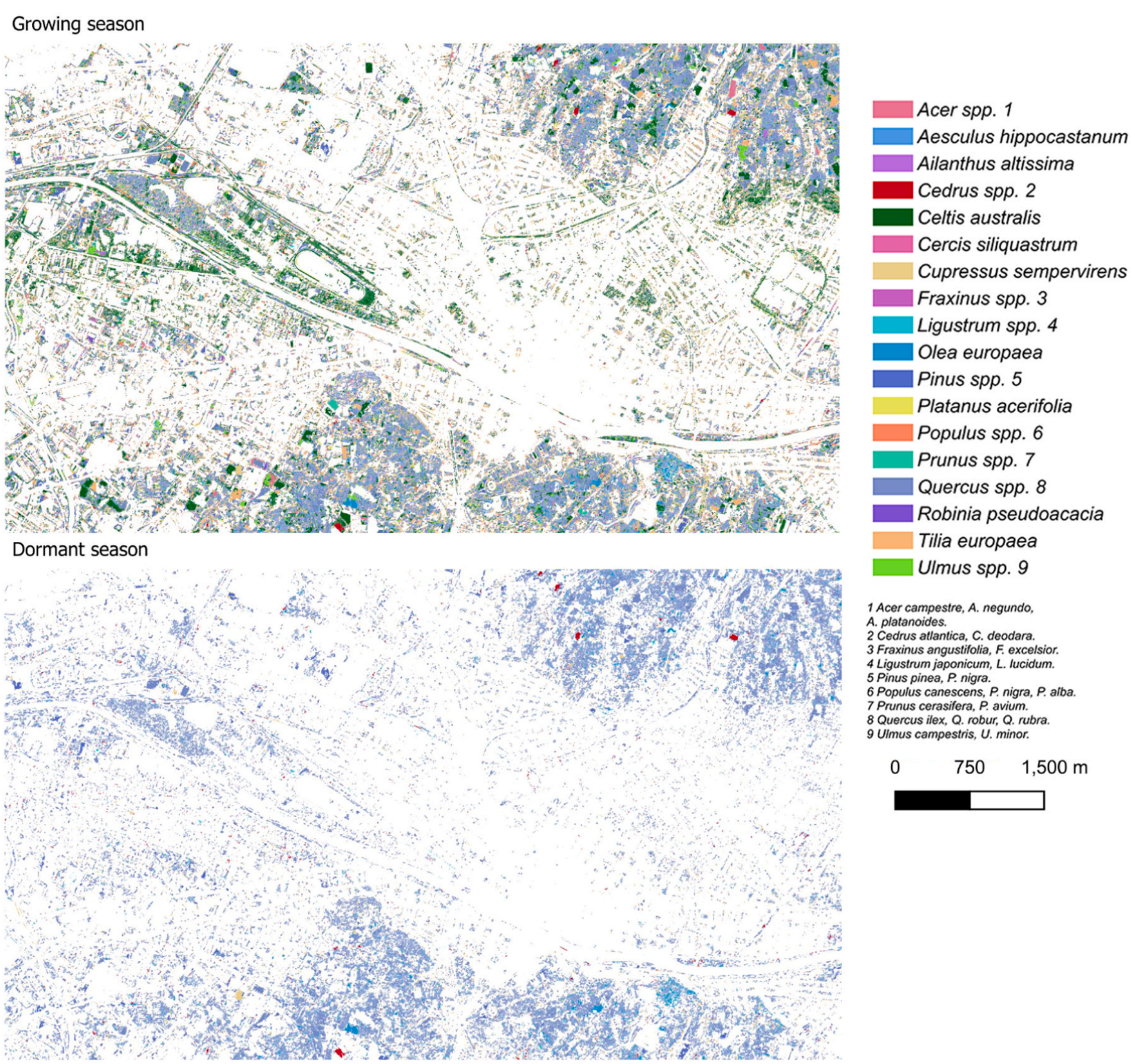

Fig. 2. Tree inventory of Florence city, Italy, during the growing and dormant seasons. Deciduous species were excluded in the dormant season.

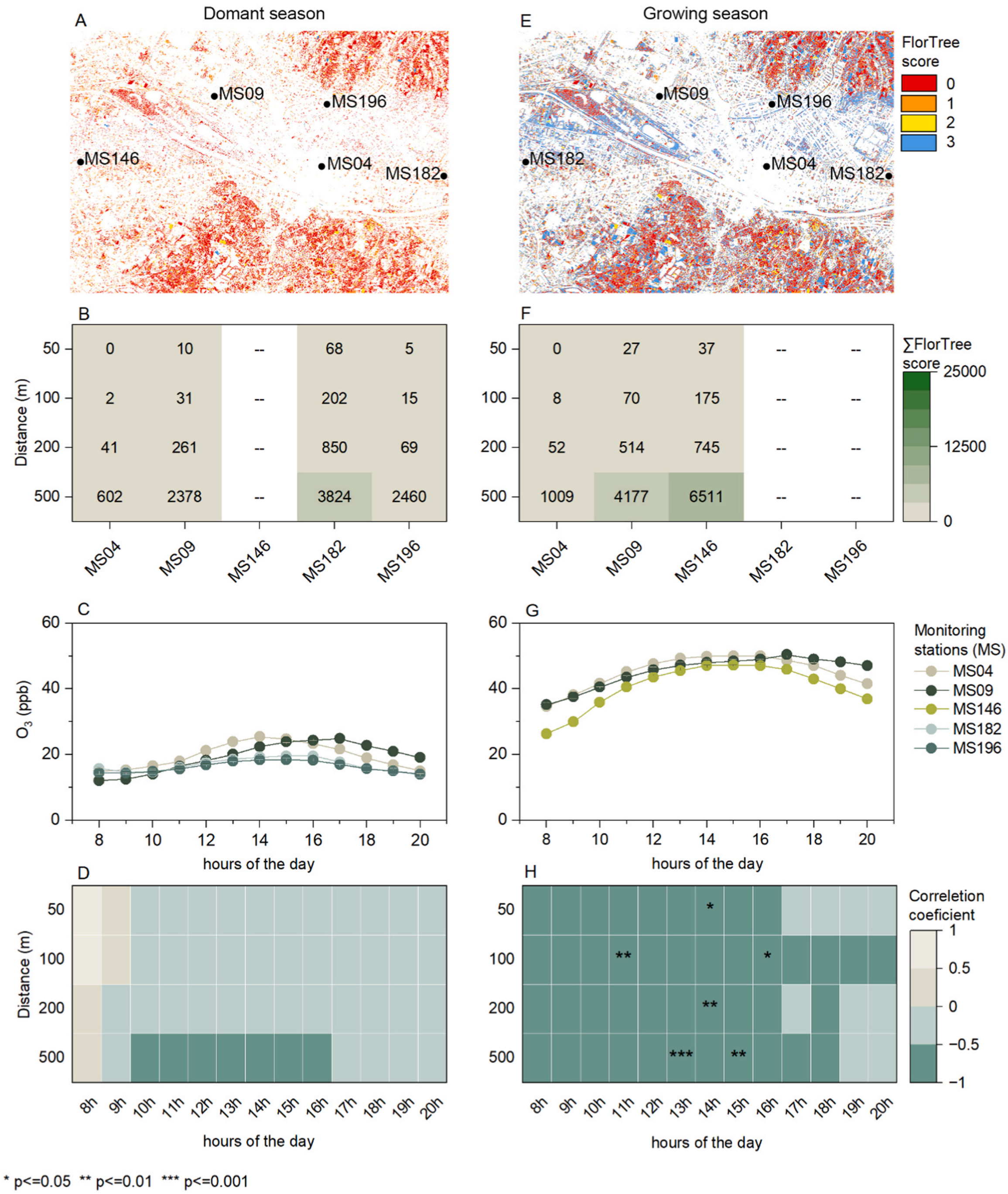

Fig. 3. Panels A and E show the spatial distribution of vegetation capacity to remove ozone (O_3) in Florence. Panels B and F indicate FlorTree scores based on distances from monitoring stations (dots in A and E). Panels C and G illustrate the daily fluctuation of O_3 levels at various monitoring sites. Lastly, panels D and H represent the relationship between local hourly O_3 levels and the removal performance of nearby vegetation. Sections A–D portray the dormant season, whereas sections E–H correspond to the growing season.

to the summer growing season (from 21st Jun to 21st September 2022) and winter dormant season of 2022 (from 1st January to 21st March 2022), and by applying the 50, 100, 200, and 500 m buffers described above; days/stations with missing or flagged values were excluded to ensure replicability. Other influencing factors (traffic, meteorology, urban form) were not explicitly accounted for; instead, only monitoring stations located inside the urban zone were retained to limit external variability.

5.1.1. *Ozone*

The Florence mapping classifying the vegetation capacity for O_3 removal shows that the city area analyzed is mostly covered by tree species not indicated for removing O_3 (FlorTree score = 0, Fig. 3A and B), as they are mostly represented by large areas covered by the evergreen species *Q. ilex*, which is a high monoterpene emitter (emission rate range: 6–58 $\mu g/g_{dw}/h$; Street et al., 1997) and thus can contribute to the local O_3 formation (Calfapietra et al., 2013; Fitzky et al., 2019).

As expected, the O_3 levels follow a daily trend, with the highest values recorded during the growing season, specifically from midday to 6 pm (Fig. 3C), reaching hour averages above 40 ppb. Ozone levels are much lower during the dormant season (Fig. 3G), with values not reaching 40 ppb throughout the day and with less variability among

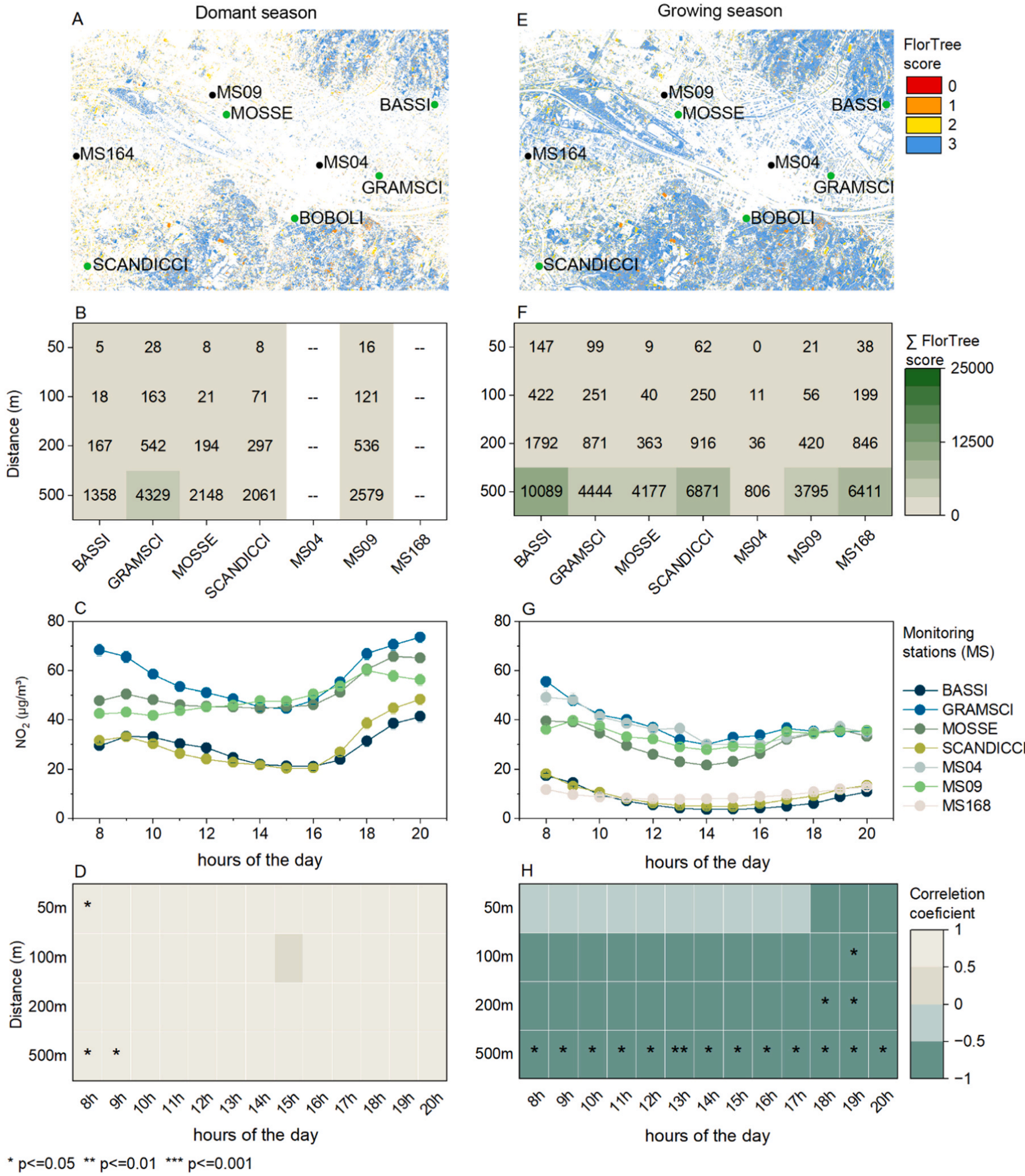

Fig. 4. Panels A and E show the spatial distribution of vegetation capacity to absorb nitrogen dioxide (NO_2) in Florence. Panels B and F indicate FlorTree scores based on distances from monitoring stations (dots in A and E). Panels C and G illustrate the daily fluctuation of NO_2 levels at various monitoring sites. Lastly, panels D and H represent the relationship between local hourly NO_2 levels and the removal performance of nearby vegetation. Sections A–D portray the dormant season, whereas sections E–H correspond to the growing season.

hours.

We verified that lower FlorTree scoring were related to low levels of O_3 ($p < 0.05$, for the growing season), suggesting that tree selection can significantly influence local air quality, with the effect varying between the hours depending on the distance between the monitoring stations (Fig. 3H). As highlighted in broader research, the capacity of urban forests to remove O_3 is influenced by tree type, canopy structure, and environmental conditions (Sicard et al., 2018), and selecting the appropriate species can significantly enhance the effectiveness of this valuable air quality improvement strategy (Sicard et al., 2022). During the dormant season, the correlations were not significant (Fig. 3D).

5.1.2. Nitrogen dioxide

The Florence mapping classifying the vegetation capacity for NO_2 removal shows that the city area analyzed is mostly covered by tree species indicated for NO_2 removal (FlorTree score = 3, Fig. 4A and E). The scoring (Fig. 4B and F) is mostly attributed to the large areas covered by the species *Q. ilex*, *Tilia* spp., and *Celtis* spp. These species present high stomatal rates and, thus, high NO_2 uptake.

The NO_2 levels follow a daily trend, with the highest values registered during the dormant season from 8 to 10 am and 6 and 8 pm, possibly related to vehicular emission during rush hours and heating systems (Fig. 4C). During the growing season, the levels decline, and the picks are not clear (Fig. 4G). However, the variation of NO_2 levels

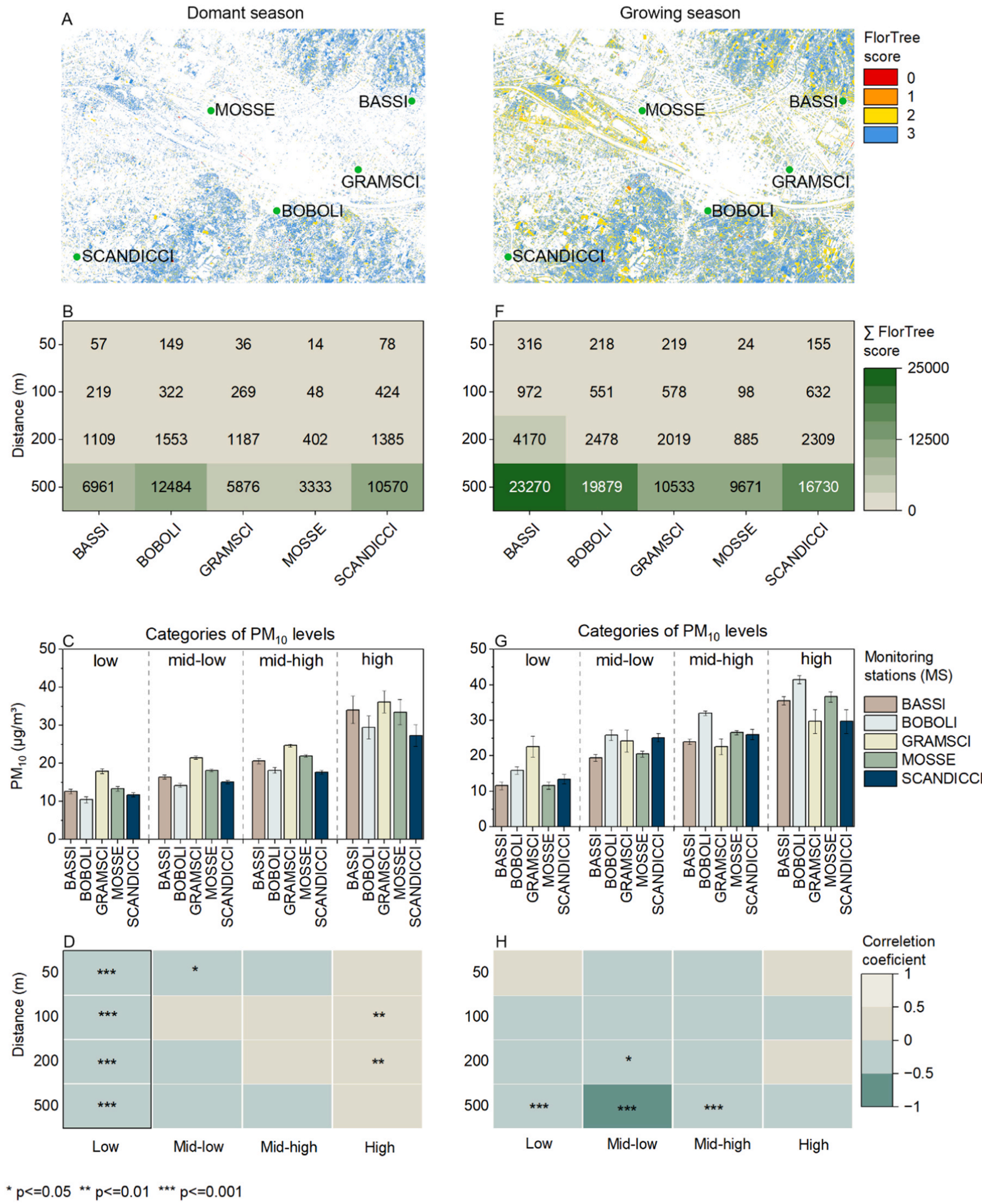

Fig. 5. Panels A and E show the spatial distribution of vegetation capacity to accumulate particulate matter (PM_{10}) in Florence. Panels B and F indicate FlorTree scores based on distances from monitoring stations (dots in A and E). Panels C and G illustrate the daily fluctuation of PM_{10} levels at various monitoring sites. Lastly, panels D and H represent the relationship between local hourly PM_{10} levels and the removal performance of nearby vegetation. Sections A–D portray the dormant season, whereas sections E–H correspond to the growing season.

between the monitoring stations can be considered large, with values ranging from 4 to 24 μg/m^3 in the growing season and 16–33 μg/m^3 during the dormant season.

We verified a negative correlation between the FlorTree scoring and the levels of NO_2 during all daily hours in the summer season of 2022, with statistical significance ($p < 0.05$) for all hours considering the distance of 500 m from the monitoring stations, varying between the hours depending on the from the monitoring stations (Fig. 4H). During the dormant season, the correlations were positive but significant ($p < 0.05$) only during the first hours in the morning (Fig. 4D), possibly indicating a dispersion issue when NO_2 levels are higher.

5.1.3. Particulate matter

To evaluate the efficacy of urban greenery in mitigating PM_{10} concentrations in the atmosphere, the dataset was stratified into four categories based on PM_{10} levels. The first category (low) includes instances where at least three of the five monitoring stations recorded PM_{10} levels below 15 μg/m^3. The second category (mid-low) encompasses instances where at least three of the five monitoring stations reported PM_{10} concentrations between 16 and 20 μg/m^3. The third category (mid-high) consists of instances where at least three of the five monitoring stations observed PM_{10} levels between 21 and 30 μg/m^3. Finally, the fourth category (high) includes instances where at least three of the five monitoring stations measured PM_{10} concentrations exceeding 30 μg/m^3.

For PM_{10}, a negative correlation ($p < 0.001$) was observed when the PM_{10} levels were low. When high levels of PM_{10} were registered, the correlation was positive ($p < 0.01$), indicating a decrease in PM_{10} dispersion due to the high density of the plant canopy (Fig. 5).

5.2. Urban vegetation as a tool for soil pollution control through phytoremediation: case studies in Italy

Soil contamination, is a global widespread concern affecting both industrialized and non-industrialized countries, which is extremely harmful to both human and environmental health. These so-called "brownfields" represent a complex issue for urban managers. Because of the low economic value of these sites, many have not been claimed for ownership or development, thereby resulting in a lack of knowledge about contamination levels in polluted soils (Wang et al., 2023). Brownfields usually contain a complex mix of compounds, mainly organic and inorganic pollutants. Traditional brownfield remediation and redevelopment approaches are based on high-maintenance techniques (e.g., excavation and off-site disposal, thermal desorption, chemical treatments, solidification/stabilization), which show high reclamation performances but are in many cases expensive and display a high environmental footprint (Hou et al., 2023). Due to these shortcomings, new approaches have been proposed for managing these areas. One of the most promising is phytoremediation because of its low environmental footprint, operational cost, high social acceptability, and potential to provide several ecosystem services (Guidi Nissim et al., 2023). The technology is very simple, relying basically on living plants and their associated rhizosphere and endophytic microorganisms to clean up (i.e., degradation, removal, or stabilization) polluted soil. However, specific aspects, including the long time taken to achieve remediation goals, often limit its application on a real field scale.

Five main phytoremediation approaches are possible based on the nature of the contaminant and the interaction established with the plant (Shmaefsky, 2020). Inorganic contaminants, such as metalloids and heavy metals, are either taken up by the roots, translocated to aerial parts (shoots and leaves) and removed off site (phytoextraction) or their solubility and mobility within the rhizosphere can be dramatically reduced by the production of specific metabolites by the plant roots (phytostabilization). Organic contaminants are mainly targeted with degradation or volatilization strategies. The former (phytodegradation) is frequently assisted by microorganisms take-up and transformation of contaminants into less harmful compounds. The latter (phytovolatilization) occurs when plants can take up the pollutant and transpire it to the atmosphere as a gas, hence removing it from the site. Another common technique is rhizodegradation, where soil contaminants are broken down by external plant processes mediated by microbial activity, and the plant basically sustains these communities by providing nutrients.

Many plant species have been investigated for phytoremediation, most of them belonging to different families and having different habitus. In a recent review, Capuana (2020) recorded more than 80 ornamental species commonly used in urban greening, which have been proven suitable for some type of phytoremediation. Among them, 23 trees, 11 shrubs, and 27 herbaceous species are suitable for phytoremediation of inorganic pollutants, whereas 6 trees, 3 shrubs, and 17 herbaceous species are suitable for remediation of organic pollutants. Noteworthy is that some species represent common species in urban green infrastructures. For instance, trees like *Betula pendula* Roth., *Cinnamomum camphora* (L.) J. Presl., *Eucalyptus camaldulensis* Dehnh., *Fraxinus excelsior* L., *Populus alba* L., *Populus nigra* L., *Salix viminalis* L. frequently used in urban gardens and parks, show some efficiency in heavy metal phytoextraction or phytostabilization. Likewise, some common shrubs belonging to the genus *Lonicera*, *Buddleja*, *Euonimus*, and *Osmanthus* show an avenue for heavy metal phytoremediation in urban settings. The choice of herbaceous plants for phytoremediation of inorganic compounds is also very wide, and many reported species (e.g., *Amaranthus caudatus* L., *Helianthus annuus* L., *Iris pseudacorus* L., *Salvia splendens* Sellow *ex* Nees, *Tagetes erecta* L., *Sedum alfredi* Hance) are commonly used in urban parks for their high aesthetic value. Trees belonging to the Salicaceae family (*Populus* and *Salix*) are also very efficient as phytoremediation of organic compounds (e.g., herbicides, TCE, PAH, PCB) as well as some shrubs (*Cytisus striatus* (Hill) Rothm., *Nerium oleander* L.) and herbaceous plants *(Aster amellus* L., *Dianthus chinensis* L., *Lolium arundinaceum* (Schreb.) Darbysh. and *Medicago sativa* L.).

In Italy, soil contamination affects about 4689 brownfield sites spread out in several regions (Araneo et al., 2021), often within or in the neighbourhoods of cities. This has stimulated in the last decades the application of different technologies in several regions, some of them providing valuable scientific information (Table 4).

Very few studies carried out in Italy have dealt specifically with phytoremediation of organic contaminants at a field scale. A rhizoremediation approach using different poplar (*Populus* spp.) clones and bacterial strains in the Fiume Sacco Valley near Rome, polluted by hexachlorocyclohexane (HCH), reported a significant decrease (– 57 %) in soil γ-HCH concentration after two years (Bianconi et al., 2011).

A higher number of applied field studies have been conducted in Italy on sites polluted by inorganic contaminants. Four species, including *Populus* × *canadensis* Moench, *Salix matsudana* Koidz., *Medicago sativa* L., and *Cannabis sativa* L., were tested for the phytoextraction of Cu, Pb, and Zn on a site belonging to the Italian Navy Base located in Southern Italy. Poplar and willow were able to extract and accumulate the highest amount of Zn (3200 and 5200 g ha^{-1} year^{-1}, respectively) and Cu (182 and 116 g ha^{-1} year^{-1}), whereas hemp, with 36 g ha^{-1} year^{-1}, showed the best phytoextraction potential for Pb (Guidi Nissim et al., 2018). The same authors also reported that despite these positive results, the total concentration of soil trace elements was not significantly reduced after 2 years, highlighting important challenges to be addressed by further investigation. Another study was conducted near Venice (Porto Marghera) contaminated by toxic elements (Cd, Hg, Zn) using two agronomic plant species with high annual biomass yield (*Helianthus annuus* L., *Brassica juncea* (L.) Czern) and chelating agents (Guarino and Sciarrillo, 2017). *Brassica juncea* was able to remove all pollutants more than twice compared to *H. annuus*. Also, adding EDTA and Ammonium Thiosulfate positively enhanced the phytoextraction rates of all pollutants. Also, species from the Poaceae family have been tested for soil phytoextraction of inorganic pollutants. Giant reed (*Arundo donax* L.) inoculated with *Trichoderma harzianum* A6 was successfully used for the removal of Cd from a polluted soil near Naples (Fiorentino et al., 2013). The same species, along with switchgrass (*Panicum virgatum* L.) and mixed spontaneous meadows, was also investigated in another trial carried out in Northern Italy (Brescia) on the Caffaro area to remove heavy metals from the soil. *Arundo donax* was the best choice for phytoextraction, being able to take up the highest amounts of Zn and Cu (3.87 and 2.09 kg ha^{-1}, respectively), also providing a valuable amount of biomass that could be potentially used for energy purposes (Danelli et al., 2021).

Other information originates from field studies carried out on sites characterized by mixed (i.e., organic and inorganic) contamination. The Monviso (*P. generosa* × *P. nigra*) poplar clone was used on a very polluted site located in the city of Taranto (Southern Italy) characterized by the co-occurrence of organic (PBC) and inorganic (Heavy Metal - HM) contamination. Results show that 2.5 years after planting a significant decrease in the overall soil HM concentration was observed compared to the initial values, highlighting HM concentrations under the national regulatory thresholds. Moreover, the poplar hybrid genotype Monviso

Table 4
The main research projects on phytoremediation carried out in Italy on a field scale.

Systems Studied	Italian City/ Region	Pollutant	Target Soil pollutant	Phytoremediation approach	Key Findings	Public Policy Implications	Reference
Rhizoremediation of soil contaminated with hexachlorocyclohexane (HCH) isomers	Valle del Sacco / Lazio	Organic	Hexa-chlorocyclohexane (HCH)	Rhizoremediation / Phytodegradation	Significant decrease in soil γ-HCH concentration after two years	Emphasize that improvement of the inoculation techniques may provide a better distribution of degrading bacteria in the contaminated soil	Bianconi et al., 2011
Heavy metal extraction by *Populus* × *canadensis*, *Salix matsudana*, *Medicago sativa* and *Cannabis sativa*	Taranto/ Apulia	Inorganic	Cu, Pb, Zn	Phytoextraction	Poplar and willow are able to extract and accumulate the highest amount of Zn and Cu, whereas hemp show the best phytoextraction potential for Pb.	Strategies enhancing metal availability for the plant are essential to increase the functionality of the system	Guidi Nissim et al., 2018
Phytoremediation using *Helianthus annuus* and Brassica juncea and chelating agents on a multicontaminated industrial site	Porto Marghera/ Veneto	Inorganic	Cd, Hg, Zn	Phytoextraction	*B. juncea* is able to remove more than twice than *H. annuus*. EDTA and Ammonium Thiosulfate are favorable for enhancing heavy metal phytoextraction	The increase of bioavailable fraction of potentially toxic elements in soil by adding synthetic chelator can be reduced effectively in a short period of time, and with the affordable costs of regular agronomic practices	Guarino and Sciarrillo, 2017
Giant reed (*Arundo donax*) in association with *Trichoderma harzianum* and compost fertilisation for Cd phytoextraction	Acerra/ Campania	Inorganic	Cd	Phytoextraction	Giant reed is suitable for assisted phytoremediation with the use of compost fertilization and *T. harzianum*.	Further research is needed to assess the residual effects of the treatments on Cd bioavailability and on the phytoremediation efficiency in the long term	Fiorentino et al., 2013
Giant reed, switchgrass (*Panicum virgatum*), and mixed spontaneous meadows for phytoremediation of heavy metals and biomass production	Brescia/ Lombardy	Inorganic	Heavy metals	Phytoextraction	Giant reed was the best performing species for Zn and Cu phytoextraction	Possibility to use the biomass for bioenergy	Danelli et al., 2021
P. generosa × *P. nigra* on soil contaminated by PBC and HMs	Taranto/ Apulia	Mixed	PBC, Heavy metals	Phytodegradation/ Phytostabilization	Monviso promoted PCB degradation and HM stabilization	Understanding of the plant–microbial consortia in the rhizosphere will enhance our ability to engineer plants for phytostrategic purposes	Ancona et al., 2017 Ancona et al., 2020 Ancona et al., 2021
The phytoremediation of an organic and inorganic polluted soil using *Populus alba*, *Cytisus scoparius* and *Paulownia tomentosa*	San Giuliano Terme/ Tuscany	Mixed	Zn, Pb, Cd, Ni, Cu, Cr, TPH, PCB	Phytodegradation/ Phytoextraction	*Paulownia tomentosa* and *Populus alba* were the most efficient species	The remediation process is efficient both in terms of contaminant removal and in soil quality improvement	Macci et al., 2016
Phytoremediation of dredged marine sediment	Livorno/ Tuscany	Mixed	TPH and Heavy metals	Phytodegradation/ Phytoextraction	Significant reduction in contaminants was obtained in planted sediments	Plant-root activity promoted the sediment transformation into a soil-like matrix	Masciandaro et al., 2014

promoted PCB degradation through rhizodegradation operated by several occurring bacteria able to transform PCBs. These findings suggested that this hybrid can be used for efficient control of HM phytostabilisation and PCB phyto/rhizodegradation (Ancona et al., 2017; Ancona et al., 2020, Ancona et al., 2021). Another experience was conducted in Central Italy (Pisa) using three common urban ornamental plant species, *Populus alba* L., *Cytisus scoparius* (L.) Link, and *Paulownia tomentosa* (Thunb.) Steud., on a soil polluted by HMs (Zn, Pb, Cd, Ni, Cu, Cr), TPHs, and PCBs. *Paulownia tomentosa* and *Populus alba* were the most efficient species in contaminant removal, suggesting their suitability as species for phytoremediation of urban polluted soils (Macci et al., 2016). Finally, phytoremediation has been investigated in Italy for the reclamation of polluted dredged marine sediments. Different trials were carried out around the port of Livorno in Central Italy, showing the potential of different plant species (*Paspalum vaginatum* Sw., *Spartium junceum* L., *Tamarix gallica* L.) and combinations in containing both organic (TPHs) and inorganic (HM) pollutants (Doni et al., 2013; Masciandaro et al., 2014; Doni et al., 2015).

This overview highlights active research in phytoremediation in many Italian regions, also showing that considerable research efforts are currently addressed to evaluate the performance of these technologies under actual field conditions. In addition, in the last few years, the use of plants for the reclamation of urban brownfields has been considered as a tool to provide ecosystem services. In this regard, more research is needed in the future to assess the actual role of this technology on several environmental (and economical) benefits potentially provided including soil quality and regeneration, regulating urban temperature, urban hydrology, carbon sequestration, air pollution control, noise attenuation, and social benefits also evaluating potential disservices related to release of specific bVOC and allergenics in the atmosphere in urban settings (Guidi Nissim, Labrecque.,2021).

6. Conclusions

This review presents the crucial role of urban greenery in improving air and soil quality in Italy and highlights the importance of incorporating urban planning and environmental policies for sustainable and healthier cities.

Scientific knowledge regarding urban green ecosystem services enables us to look at urban green as an effective strategy for pollution mitigation across different urban contexts. Considering the close relationships and interdependencies between air and soil compartments in urban settings, urban forestry planning strategies should consider both elements to ensure the health of vegetation and maximize its effects on pollution reduction. However, several limitations remain insufficiently quantified, such as (1) empirical studies not well geographically distributed, (2) experiments often of short duration, and (3) potential urban green disservices, including; the presence of high bVOC emission species, that may exacerbate O_3 formation; use of allergenic pollen species; or reduced pollutant dispersion under dense canopies. Futhermore, uncertainties in soil contaminant baselines and the long term required for effective phytoremediation further constrain the generalization of these results.

Based on the evidence reviewed, we recommend for policy and practice to (1) discuss and promote long term monitoring networks, especially to verify the capacity to cope air pollution and improve soil quality in new GI; (2) optimize species selection based on scientific evidences and following dedicated guidelines; (3) create participatory governance and dedicated funding streams to ensure maintenance, risk management and adaptive management that address emerging climate stresses.

Future research should address key gaps and implementation challenges by developing coupled atmosphere–soil–vegetation models, as well as standardizing metrics and protocols for measuring pollutant removal and soil recovery. Additional priorities include advancing high-resolution species mapping tools for decision support. Addressing these challenges will improve scalability, reduce uncertainty and help fully realize the pollution-mitigation potential of urban vegetation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used OpenAI/ ChatGPT and Grammarly to improve the manuscript's readability and language. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

CRediT authorship contribution statement

Werther Guidi Nissim: Writing – original draft, Investigation, Data curation, Conceptualization. **Barbara Baesso Moura:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Scartazza:** Writing – original draft, Investigation. **Jacopo Manzini:** Writing – review & editing, Investigation. **Alessandra De Marco:** Writing – original draft, Investigation. **Alessandro Zaldei:** Investigation, Data curation. **Peoletti Elena:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Pierre Sicard:** Writing – original draft, Investigation. **Yasutomo Hoshika:** Writing – original draft, Supervision, Conceptualization. **Massimo Labra:** Project administration, Conceptualization.

Declaration of Competing Interest

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

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References

Ajmone-Marsan, F., Padoan, E., Madrid, F., Vrščaj, B., Biasioli, M., Davidson, C.M., 2019. Metal release under anaerobic conditions of urban soils of four european cities. Water Air Soil Pollut. 230, 1–16. https://doi.org/10.1007/s11270-019-4101-5.

Ancona, V., Caracciolo, A.B., Campanale, C., Rascio, I., Grenni, P., Di Lenola, M., Bagnuolo, G., Uricchio, V.F., 2020. Heavy metal phytoremediation of a poplar clone in a contaminated soil in Southern Italy. J. Chem. Technol. Biotechnol. 95 (4), 940–949. https://doi.org/10.1002/jctb.6145.

Ancona, V., Caracciolo, A.B., Grenni, P., Di Lenola, M., Campanale, C., Calabrese, A., Uricchio, V.F., Mascolo, G., Massacci, A., 2017. Plant-assisted bioremediation of a historically PCB and heavy metal-contaminated area in Southern Italy. N. Biotechnol. 38, 65–73. https://doi.org/10.1016/j.nbt.2016.09.006.

Ancona, V., Rascio, I., Aimola, G., Campanale, C., Grenni, P., Lenola, M.D., Garbini, G.L., Uricchio, V.F., Barra Caracciolo, A., 2021. Poplar-assisted bioremediation for recovering a PCB and heavy-metal-contaminated area. Agriculture 11 (8), 689. https://doi.org/10.3390/agriculture11080689.

Araneo, F., Bartolucci, E., Vecchio, A., 2021. Synthesis of the report "Status of contaminated sites management in Italy: regional data" lo stato delle bonifiche dei siti contaminati in italia: I dati regionali - edizione. ISPRA Rapp. 337 (21), 2021.

Arias-Navarro, C., Panagos, P., Jones, A., Amaral, M.J., Schneegans, A., Van Liedekerke, M., Montanarella, L., 2023. Forty years of soil research funded by the european commission: trends and future. A systematic review of research projects. Eur. J. Soil Sci. 74 (5), e13423. https://doi.org/10.1111/ejss.13423.

Bae, J., Ryu, Y., 2015. Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park. Landsc. Urban Plan. 136, 57–67.

Bianconi, D., De Paolis, M.R., Agnello, A.C., Lippi, D., Pietrini, F., Zacchini, M., et al., 2011. Field-scale rhyzoremediation of a contaminated soil with hexachlorocyclohexane (HCH) isomers: the potential of poplars for environmental restoration and economical sustainability. Handb. Phytoremediat. 1–12.

Biasioli, M., Ajmone-Marsan, F., 2007. Organic and inorganic diffuse contamination in urban soils: the case of Torino (Italy). J. Environ. Monit. 9 (8), 862–868. https://doi.org/10.1039/b705285e.

Bottalico, F., Travaglini, D., Chirici, G., Garfì, V., Giannetti, F., De Marco, A., Fares, S., Marchetti, M., Nocentini, S., Paoletti, E., Salbitano, F., Sanesi, G., 2017. A spatially-explicit method to assess the dry deposition of air pollution by urban forests in the city of florence, Italy. Urban For. Urban Green. 27, 221–234. https://doi.org/10.1016/j.ufug.2017.08.013.

Bretzel, F., Calderisi, M., 2006. Metal contamination in urban soils of coastal tuscany (Italy). Environ. Monit. Assess. 118, 319–335.

Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., Loreto, F., 2013. Role of biogenic volatile organic compounds (BVOC) emitted by urban trees on ozone concentration in cities: a review. Environ. Pollut. 183, 71–80. https://doi.org/10.1016/j.envpol.2013.03.012.

Canedoli, C., Ferrè, C., El Khair, D.A., et al., 2020. Soil organic carbon stock in different urban land uses: high stock evidence in urban parks. Urban Ecosyst. 23, 159–171. https://doi.org/10.1007/s11252-019-00901-6.

Capuana, M., 2020. A review of the performance of woody and herbaceous ornamental plants for phytoremediation in urban areas. iForest 13, 139–151. https://doi.org/10.3832/ifor3242-013.

Cardelli, R., Vanni, G., Marchini, F., Saviozzi, A., 2017. Characterization and origin of organic and inorganic pollution in urban soils in pisa (Tuscany, Italy). Environ. Monit. Assess. 189, 1–17. https://doi.org/10.1007/s10661-017-6264-0.

Cenci, R.M., Dabergami, D., Beccaloni, E., Ziemacki, G., Benedetti, A., Pompili, L., Melina, A.S., Bianchi, M., 2008. Bioindicatori per valutare la qualità dei suoli di alcuni parchi della città di roma. JRC Scientific and Technical Report. Office for Official Publications of the European Union.
Cicchella, D., De Vivo, B., Lima, A., 2003. Palladium and platinum concentration in soils from the napoli metropolitan area, Italy: possible effects of catalytic exhausts. Sci. Total Environ. 308 (1-3), 121–131. https://doi.org/10.1016/S0048-9697(02)00632-0.
Cicchella, D., De Vivo, B., Lima, A., Albanese, S., McGill, R.A.R., Parrish, R.R., 2008. Heavy metal pollution and pb isotopes in urban soils of napoli, Italy. Geochem. Explor. Environ. Anal. 8 (1), 103–112. https://doi.org/10.1144/1467-7873/07-148.
Cicchella, D., Zuzolo, D., Albanese, S., Fedele, L., Di Tota, I., Guagliardi, I., Thiombane, M., De Vivo, B., Lima, A., 2020. Urban soil contamination in salerno (Italy): concentrations and patterns of major, minor, trace and ultra-trace elements in soils. J. Geochem. Explor. 213, 106519. https://doi.org/10.1016/j.gexplo.2020.106519.
Comune-di-Padova, 2022. Buone pratiche per la progettazione del verde urbano. Piano Del. Verde Del. Comune di Padova. ⟨https://www.comune.padova.it/piano-del-verde-comunale/20_ALL-09_BuonePratiche.pdf⟩.
Danelli, T., Sepulcri, A., Masetti, G., Colombo, F., Sangiorgio, S., Cassani, E., Anelli, S., Adani, F., Pilu, R., 2021. *Arundo donax* L. Biomass production in a polluted area: effects of two harvest timings on heavy metals uptake. Appl. Sci. 11 (3), 1147. https://doi.org/10.3390/app11031147.
De Guidi, G., Falciglia, P.P., Catalfo, A., De Guidi, G., Fagone, S., Vagliasindi, F.G., 2017. Soil contaminated with PAHs and nitro-PAHs: contamination levels in an urban area of catania (Sicily, Southern Italy) and experimental results from simulated decontamination treatment. Clean. Technol. Environ. Policy 19, 1121–1132.
De Lucia, B., Cristiano, G., Vecchietti, L., Bruno, L., 2013. Effect of different rates of composted organic amendment on urban soil properties, growth and nutrient status of three Mediterranean native hedge species. Urban For. Urban Green. 12 (4), 537–545. https://doi.org/10.1016/j.ufug.2013.07.008.
Denora, M., Mehmeti, A., Candido, V., Brunetti, G., De Mastro, F., Murgolo, S., Perniola, M., 2024. Fate of emerging contaminants in the soil-plant system: a study on durum wheat irrigated with treated municipal wastewater. Front. Soil Sci. 4, 1448016.
Diana, A., Bertinetti, S., Abollino, O., Giacomino, A., Buoso, S., Favilli, L., et al., 2022. PM10 element distribution and environmental-sanitary risk analysis in two Italian industrial cities. Atmosphere 14 (1), 48. https://doi.org/10.3390/atmos14010048.
Doni, S., Macci, C., Peruzzi, E., Iannelli, R., Ceccanti, B., Masciandaro, G., 2013. Decontamination and functional reclamation of dredged brackish sediments. Biodegradation 24, 499–512. https://doi.org/10.1007/s10532-012-9606-1.
Doni, S., Macci, C., Peruzzi, E., Iannelli, R., Masciandaro, G., 2015. Heavy metal distribution in a sediment phytoremediation system at pilot scale. Ecol. Eng. 81, 146–157. https://doi.org/10.1016/j.ecoleng.2015.04.049.
Edeigba, B.A., Ashinze, U.K., Umoh, A.A., Biu, P.W., Daraojimba, A.I., 2024. Urban Green spaces and their impact on environmental health: a global review. World J. Adv. Res. Rev. 21, 917–927. https://doi.org/10.30574/wjarr.2024.21.2.0518.
Eldridge, D.J., Cui, H., Ding, J., et al., 2024. Urban greenspaces and nearby natural areas support similar levels of soil ecosystem services. npj Urban Sustain 4, 15. https://doi.org/10.1038/s42949-024-00154-z.
Emilia-Romagna, 2025. Alberi per la città: Un abaco per l'infrastruttura verde urbana. Osservatorio Regionale per la Qualità del Paesaggio – Regione Emilia-Romagna – Direzione Generale Cura del Territorio e dell'Ambiente. ⟨https://serviziambiente.regione.emilia-romagna.it/abalberi/Volume_alberi_pagina_singola.pdf⟩.
Esposito, F., Memoli, V., Panico, S.C., Di Natale, G., Trifuoggi, M., Giarra, A., Maisto, G., 2020. Leaf traits of quercus ilex L. Affect particulate matter accumulation. Urban For. Urban Green. 54, 126780. https://doi.org/10.1016/j.ufug.2020.126780.
European Commission ,2006. Thematic Strategy for Soil Protection. COM (2006) 231 final, 22.9.2006. Brussels, Belgium.
European Commission ,2020. EU Biodiversity Strategy for 2030. Bringing nature back into our lives. Brussels, 20.5.2020 COM(2020) 380 final.
European Commission ,2021. Directorate-General for Communication, 3 Billion Trees by 2030. Publications Office of the European Union. ⟨https://data.europa.eu⟩.
European Environment Agency ,2023. "Harm to human health from air pollution in Europe: burden of disease 2023". EEA Briefing no. 23/2023. ISBN: 978-92-9480-614-7, doi: 10.2800/721439.
EP, 2022. European Parliament & Council of the European Union. Regulation (EU) 2022/869 of 30 MayMay 30 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013. Official Journal of the European Union, L 152, 45–109. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022R0869.
EP, 2024. European Parliament & Council of the European Union. Regulation (EU) 2024/1991 of 24 JuneJune 24 2024 on nature restoration and amending Regulation (EU) 2022/869. Official Journal of the European Union, L 1991, 1–93. https://data.europa.eu/eli/reg/2024/1991/oj.
European Parliament and Council. (2024). Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast). Official Journal of the European Union, L 2024/2881, 20.11.2024.
Fabietti, G., Biasioli, M., Barberis, R., Ajmone-Marsan, F., 2010. Soil contamination by organic and inorganic pollutants at the regional scale: the case of piedmont, Italy. J. Soils Sediment. 10, 290–300. https://doi.org/10.1007/s11368-009-0114-9.
Fares, S., Conte, A., Alivernini, A., Chianucci, F., Grotti, M., Zappitelli, I., et al., 2020. Testing removal of carbon dioxide, ozone, and atmospheric particles by urban parks in Italy. Environ. Sci. Technol. 54 (23), 14910–14922. https://doi.org/10.1021/acs.est.0c04740.
Fiorentino, N., Fagnano, M., Adamo, P., Impagliazzo, A., Mori, M., Pepe, O., et al., 2013. Assisted phytoextraction of heavy metals: compost and trichoderma effects on giant reed (Arundo donax L.) uptake and soil N-cycle microflora. Ital. J. Agron. 8 (4), e29. https://doi.org/10.4081/ija.2013.e29.
Fitzky, A.C., Sandén, H., Karl, T., Fares, S., Calfapietra, C., Grote, R., et al., 2019. The interplay between ozone and urban vegetation—BVOC emissions, ozone deposition, and tree ecophysiology. Front. For. Glob. Change 2, 50 (https://doi.org/).
Fusaro, L., Marando, F., Sebastiani, A., Capotorti, G., Blasi, C., Copiz, R., et al., 2017. Mapping and assessment of PM_{10} and O_3 removal by woody vegetation at urban and regional level. Remote Sens. 9 (8), 791. https://doi.org/10.3389/ffgc.2019.00050.
Gaggero, E., Malandrino, M., Fabbri, D., Bordiglia, G., Fusconi, A., Mucciarelli, M., Calza, P., 2020. Uptake of potentially toxic elements by four plant species suitable for phytoremediation of turin urban soils. Appl. Sci. 10 (11), 3948.
Giaccio, L., Cicchella, D., De Vivo, B., Lombardi, G., De Rosa, M., 2012. Does heavy metals pollution affects semen quality in men? A case of study in the metropolitan area of naples (Italy). J. Geochem. Explor. 112, 218–225. https://doi.org/10.1016/j.gexplo.2011.08.009.
Grapow, L., Blasi, C., 1998. A comparison of the urban flora of different phytoclimatic regions in Italy. Glob. Ecol. Biogeogr. Lett. 7 (5), 367–378 (https://doi.org/).
Grote, R., Samson, R., Alonso, R., Amorim, J.H., Cariñanos, P., Churkina, G., Fares, S., Thiec, D.L., Niinemets, Ü., Mikkelsen, T.N., Paoletti, E., Tiwary, A., Calfapietra, C., 2016. Functional traits of urban trees: air pollution mitigation potential. Front. Ecol. Environ. 14 (10), 543–550. https://doi.org/10.1002/fee.1426.
Guagliardi, I., Cicchella, D., De Rosa, R., Buttafuoco, G., 2015. Assessment of lead pollution in topsoils of a Southern Italy area: analysis of urban and peri-urban environment. J. Environ. Sci. 33, 179–187. https://doi.org/10.1046/j.1466-822X.1998.00304.x.
Guarino, C., Sciarrillo, R., 2017. The effectiveness and efficiency of phytoremediation of a multicontaminated industrial site: porto marghera (Venice Lagoon, Italy). Chemosphere 183, 371–379. https://doi.org/10.1016/j.chemosphere.2017.05.102.
Guidi Nissim, W., Castiglione, S., Guarino, F., Pastore, M.C., Labra, M., 2023. Beyond cleansing: ecosystem services related to phytoremediation. Plants 12 (5), 1031. https://doi.org/10.3390/plants12051031.
Guidi Nissim, W., Labrecque, M., 2021. Reclamation of urban brownfields through phytoremediation: implications for building sustainable and resilient towns. Urban For. Urban Green. 65, 127364. https://doi.org/10.1016/j.ufug.2021.127364.
Guidi Nissim, W., Palm, E., Mancuso, S., Azzarello, E., 2018. Trace element phytoextraction from contaminated soil: a case study under Mediterranean climate. Environ. Sci. Pollut. Res. 25, 9114–9131. https://doi.org/10.1007/s11356-018-1197-x.
Hartig, T., Mitchell, R., De Vries, S., Frumkin, H., 2014. Nature and health. Annu. Rev. Public Health 35 (1), 207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443.
Hou, D., Al-Tabbaa, A., O'Connor, D., Hu, Q., Zhu, Y.G., Wang, L., et al., 2023. Sustainable remediation and redevelopment of brownfield sites. Nat. Rev. Earth Environ. 4 (4), 271–286. https://doi.org/10.1038/s43017-023-00404-1.
Kondo, M.C., Mueller, N., Locke, D.H., Roman, L.A., Rojas-Rueda, D., et al., 2020. Health impact assessment of Philadelphia's 2025 tree canopy cover goals. Lancet Planet. Health 4, e149–e157. https://doi.org/10.1016/S2542-5196(20)30058-9.
Lai, K.Y., Kumari, S., Gallacher, J., Webster, C., Sarkar, C., 2024. Nexus between residential air pollution and physiological stress is moderated by greenness. Nat. Cities 1, 225–237. https://doi.org/10.1038/s44284-024-00036-6.
Li, X., Shen, X., Jiang, W., Xi, Y., Li, S., 2024. Comprehensive review of emerging contaminants: detection technologies, environmental impact, and management strategies. Ecotoxicol. Environ. Saf. 278, 116420.
Lindén, L., Riikonen, A., Setälä, H., Yli-Pelkonen, V., 2020. Quantifying carbon stocks in urban parks under cold climate conditions. Urban For. Urban Green. 49, 126633.
Lopez, M.A., De Marco, A., Anav, A., Sorrentino, B., Paoletti, E., Manzini, J., Hoshika, Y., Sicard, P., 2025. The 3-30-300 rule compliance: a geospatial tool for urban planning. Landsc. Urban Plan. 261, 105396. https://doi.org/10.1016/j.landurbplan.2025.105396.
Macci, C., Peruzzi, E., Doni, S., Poggio, G., Masciandaro, G., 2016. The phytoremediation of an organic and inorganic polluted soil: a real scale experience. Int. J. Phytoremediat. 18 (4), 378–386. https://doi.org/10.1080/15226514.2015.1109595.
Macci, C., Vannucchi, F., Scartazza, A., Masciandaro, G., Doni, S., Peruzzi, E., 2025. Soil–Plant indicators for assessing nutrient cycling and ecosystem functionality in urban forestry. Urban Sci. 9 (3), 82. https://doi.org/10.2989/10220119.2020.1854345.
Madrid, F., Biasioli, M., Ajmone-Marsan, F., 2008. Availability and bioaccessibility of metals in fine particles of some urban soils. Arch. Environ. Contam. Toxicol. 55, 21–32. https://doi.org/10.1007/s00244-007-9086-1.
Manta, D.S., Angelone, M., Bellanca, A., Neri, R., Sprovieri, M., 2002. Heavy metals in urban soils: a case study from the city of palermo (Sicily), Italy. Sci. Total Environ. 300 (1-3), 229–243.
Manzini, J., Hoshika, Y., Carrari, E., Sicard, P., Watanabe, M., Tanaka, R., et al., 2023. FlorTree: a unifying modelling framework for estimating the species-specific pollution removal by individual trees and shrubs. Urban For. Urban Green. 85, 127967. https://doi.org/10.1016/j.ufug.2023.127967.
Manzini, J., Hoshika, Y., Sicard, P., De Marco, A., Ferrini, F., Pallozzi, E., et al., 2024. Detection of morphological and eco-physiological traits of ornamental woody species to assess their potential net O_3 uptake. Environ. Res. 252, 118844. https://doi.org/10.1016/j.envres.2024.118844.

Marando, F., Salvatori, E., Fusaro, L., Manes, F., 2016. Removal of PM10 by forests as a nature-based solution for air quality improvement in the metropolitan city of Rome. Forests 7 (7), 150. https://doi.org/10.3390/f7070150.

Masciandaro, G., Di Biase, A., Macci, C., Peruzzi, E., Iannelli, R., Doni, S., 2014. Phytoremediation of dredged marine sediment: monitoring of chemical and biochemical processes contributing to sediment reclamation. J. Environ. Manag. 134, 166–174. https://doi.org/10.1016/j.jenvman.2013.12.028.

Milano, V., Cortet, J., Baldantoni, D., Bellino, A., Dubs, F., Nahmani, J., et al., 2017. Collembolan biodiversity in Mediterranean urban parks: impact of history, urbanization, management and soil characteristics. Appl. Soil Ecol. 119, 428–437. https://doi.org/10.1016/j.apsoil.2017.03.022.

MATTM, 2018. Ministero dell'Ambiente e della Tutela del Territorio e del Mare. Strategia nazionale del verde urbano: Foreste urbane resilienti ed eterogenee per la salute e il benessere dei cittadini. Roma: Comitato per lo Sviluppo del Verde Pubblico. https://www.mase.gov.it/sites/default/files/archivio/allegati/comitat%20verde%20pubblico/strategia_verde_urbano.pdf.

MTE, 2022a. Ministero della Transizione Ecologica. Decreto: Criteri ambientali minimi per l'affidamento del servizio di progettazione di interventi edilizi. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale, n. 183, 6 agosto 2022 https://www.gazzettaufficiale.it/eli/gu/2022/08/06/183/sg/pdf.

MTE. 2022b. Ministero delle Transizione Ecologica. Piano di forestazione urbana ed extraurbana: Investimento 3.1 del PNRR - Tutela e valorizzazione del verde urbano ed extraurbano. Roma. https://www.gazzettaufficiale.it/eli/gu/2022/08/06/183/sg/pdf.

Mori, J., Fini, A., Galimberti, M., Ginepro, M., Burchi, G., Massa, D., Ferrini, F., 2018. Air pollution deposition on a roadside vegetation barrier in a Mediterranean environment: combined effect of evergreen shrub species and planting density. Sci. Total Environ. 643, 725–737. https://doi.org/10.1016/j.scitotenv.2018.06.217.

Moura, B.B., Zammarchi, F., Manzini, J., Hoshika, Y., Brilli, L., Vagnoli, C., et al., 2024. Assessment of seasonal variations in particulate matter accumulation and elemental composition in urban tree species. Environ. Res. 252, 118782. https://doi.org/10.1016/j.envres.2024.118782.

Muresan, A.N., Sebastiani, A., Gaglio, M., Fano, E.A., Manes, F., 2022. Assessment of air pollutants removal by Green infrastructure and urban and peri-urban forests management for a greening plan in the municipality of ferrara (Po river plain, Italy). Ecol. Indic. 135, 108554. https://doi.org/10.1016/j.ecolind.2022.108554.

Nardella, L., Sebastiani, A., Stafoggia, M., Franzese, P.P., Manes, F., 2023. Modelling PM10 removal in three Italian coastal metropolitan cities along a latitudinal gradient. Ecol. Model. 483, 110423. https://doi.org/10.1016/j.ecolmodel.2023.110423.

Orlandi, F., Fornaciari, M., Ranfa, A., Proietti, C., Ruga, L., Meloni, G., et al., 2022. LIFE-CLIVUT, ecosystem benefits of urban Green areas: a pilot case study in perugia (Italy). iFor. Biogeosci. For. 15 (2), 133. https://doi.org/10.3832/ifor3908-015.

Paudel, S., States, S.L., 2023. Urban green spaces and sustainability: Exploring the ecosystem services and disservices of grassy lawns versus floral meadows. Urban For. Urban Green. 84, 127932. https://doi.org/10.1016/j.ufug.2023.127932.

Papa, S., Bartoli, G., Nacca, F., D'Abrosca, B., Cembrola, E., Pellegrino, A., Fioretto, A., 2012. Trace metals, peroxidase activity, PAHs contents, and ecophysiological changes in *quercus ilex* leaves in the urban area of caserta (Italy). J. Environ. Manag. 113, 501–509.

Paoletti, E., 2006. Impact of ozone on Mediterranean forests: a review. Environ. Pollut. 144 (2), 463–474. https://doi.org/10.1016/j.envpol.2005.12.051.

Parvin, N., Sayeed, K.M.A., Jaman, M.S., Akter, S., Munshi, M.H., Jamil, M., Tamanna, M., 2025. Plant diversity enhances soil organic carbon content in mixed stands more than single stands in the urban vegetation of Dhaka, Bangladesh. Ecol. Front. 45 (2), 316–327.

Pataki, D.E., Alberti, M., Cadenasso, M.L., Felson, A.J., McDonnell, M.J., Pincetl, S., Pouyat, R.V., Setälä, H., Whitlow, T.H., 2013. City trees: urban greening needs better data. Nature 502, 624. https://doi.org/10.1038/502624d.

Perri, G., Gargano, D., Randazzo, L., Calabrese, S., Brusca, L., Fuoco, I., La Russa, M.F., 2024. Nature-Based options for improving urban environmental quality: using black poplar trees for monitoring heavy metals pollution in urbanized contexts. Resources 13 (6), 85.

Petrini, R., Ghezzi, L., Arrighi, S., Genovesi, L., Frassi, C., Pandolfi, L., 2022. Trace elements in soil and urban groundwater in an area impacted by metallurgical activity: health risk assessment in the historical barga municipality (Tuscany, Italy). Int. J. Environ. Res. Public Health 19 (20), 13419. https://doi.org/10.3390/ijerph192013419.

Programma nazionale di controllo dell'inquinamento atmosferico (PNCIA). Ministero dell'Ambiente e della Sicurezza Energetica, 2021. Gazzetta Ufficiale Della Repubblica Italiana, 1–165. https://www.mase.gov.it/portale/documents/d/guest/pncia_20_12_21-pdf.

Regione Emilia-Romagna – Direzione Generale Cura del Territorio e dell'Ambiente, & ART-ER Attrattività Ricerca Territorio, 2024. PAIR 2030: Documento di sintesi – Piano Aria Integrato Regionale. https://ambiente.regione.emilia-romagna.it/it/aria/pair-2030.

Regione-Piemonte – Consiglio Regionale. Piano Regionale di Qualità dell'Aria (PRQA) – Relazione generale. Deliberazione del Consiglio regionale n. 18-28783 del 10 dicembre 2024. 〈https://www.regione.piemonte.it/web/temi/ambiente-territorio/ambiente/aria/piano-regionale-qualita-dellaria-prqa#〉.

Regione Toscana. (2018) Direzione Ambiente ed Energia. Linee guida per la messa a dimora di specifiche specie arboree per l'assorbimento di biossido di azoto, materiale particolato fine e ozono. Firenze: Regione Toscana. https://www.regione.toscana.it/documents/10180/23809530/Allegato-1-LG-Piantumazione-agg.+31+dic-2021.pdf.

Russo, A., Escobedo, F.J., Zerbe, S., 2016. Quantifying the local-scale ecosystem services provided by urban treed streetscapes in bolzano, Italy. AIMS Environ. Sci. 3 (1), 58–76.

Sacchi, E., Brenna, S., Fornelli Genot, S., Leoni, A., Sale, V.M., Setti, M., 2020. Potentially toxic elements (PTEs) in cultivated soils from lombardy (Northern Italy): spatial distribution, origin, and management implications. Minerals 10 (4), 298.

Scartazza, A., Vannucchi, F., Peruzzi, E., Macci, C., Scatena, M., Manzini, J., et al., 2025. Nutrient interaction in the Soil-Plant system and tree physiological functional traits in an urban Green infrastructure. J. Soil Sci. Plant Nutr. 1–17. https://doi.org/10.3934/environsci.2016.1.58.

Sebastiani, A., Buonocore, E., Franzese, P.P., Riccio, A., Chianese, E., Nardella, L., Manes, F., 2021. Modeling air quality regulation by Green infrastructure in a Mediterranean coastal urban area: the removal of PM10 in the metropolitan city of naples (Italy). Ecol. Model. 440, 109383. https://doi.org/10.1016/j.ecolmodel.2020.109383.

Setälä, H.M., Francini, G., Allen, J.A., Hui, N., Jumpponen, A., Kotze, D.J., 2016. Vegetation type and age drive changes in soil properties, nitrogen, and carbon sequestration in urban parks under cold climate. Front. Ecol. Evol. 4, 93. https://doi.org/10.3389/fevo.2016.00093.

Sgrigna, G., Sæbø, A., Gawronski, S., Popek, R., Calfapietra, C., 2015. Particulate matter deposition on quercus ilex leaves in an industrial city of central Italy. Environ. Pollut. 197, 187–194. https://doi.org/10.1016/j.envpol.2014.11.030.

Shmaefsky, B.R., 2020. Principles of phytoremediation. In: Shmaefsky, B. (Ed.), Phytoremediation. Concepts and Strategies in Plant Sciences. Springer, Cham. https://doi.org/10.1007/978-3-030-00099-8_1.

Sialelli, J., Davidson, C.M., Hursthouse, A.S., Ajmone-Marsan, F., 2011. Human bioaccessibility of cr, cu, ni, pb and zn in urban soils from the city of Torino, Italy. Environ. Chem. Lett. 9, 197–202. https://doi.org/10.1007/s10311-009-0263-5.

Sicard, P., Pascu, I.S., Petrea, S., Leca, S., De Marco, A., Paoletti, E., Agathokleous, E., Calatayud, V., 2025. Tree canopy cover and air pollution-related mortality in european cities. Lancet Planet. Health (in press.).

Sicard, P., Agathokleous, E., Anenberg, S.C., De Marco, A., Paoletti, E., Calatayud, V., 2023. Trends in urban air pollution over the last two decades: a global perspective. Sci. Total Environ. 858, 160064. https://doi.org/10.1016/j.scitotenv.2022.160064.

Sicard, P., Agathokleous, E., Araminiene, V., Carrari, E., Hoshika, Y., De Marco, A., Paoletti, E., 2018. Should we see urban trees as effective solutions to reduce increasing ozone levels in cities? Environ. Pollut. 243, 163–176. https://doi.org/10.1016/j.envpol.2018.08.049.

Sicard, P., Agathokleous, E., De Marco, A., Paoletti, E., Calatayud, V., 2021. Urban population exposure to air pollution in Europe over the last decades. Environ. Sci. Eur. 33, 1–12. https://doi.org/10.1186/s12302-020-00450-2.

Sicard, P., Agathokleous, E., Marco, A.D., Paoletti, E., 2022. Ozone-reducing urban plants: choose carefully. Science. https://doi.org/10.1126/science.add9734.

Silli, V., Salvatori, E., Manes, F., 2015. Removal of airborne perticulate mattes by vegetation in a urban park in the city of Rome (Italy): an ecosystem service perspective. Ann. di Bot. 5, 53–62. https://doi.org/10.4462/annbotrm-13077.

Sillo, F., Neri, L., Calvo, A., Zampieri, E., Petruzzelli, G., Ferraris, I., Delledonne, M., Zaldei, A., Gioli, B., Baraldi, R., Balestrini, R., 2024. Correlation between microbial communities and volatile organic compounds in an urban soil provides clues on soil quality towards sustainability of city flowerbeds. Heliyon 10 (1), e23594. https://doi.org/10.1016/j.heliyon.2023.e23594.

SNPA – Sistema Nazionale per la Protezione dell'Ambiente. (2024). La qualità dell'aria in Italia: Edizione 2023 (Report ambientali SNPA n. 40/2024). Roma: ISPRA. ISBN 978-88-448-1207-2.

Street, R., Owen, S., Duckham, S., Boissard, C., Hewitt, C., 1997. Effect of habitat and age on variations in volatile organic compound (VOC) emissions from quercus ilex and pinus pinea. Atmos. Environ. 31, 89–100. https://doi.org/10.1016/S1352-2310(97)00077-0.

Tammekivi, T., Kaasik, M., Hamer, P., Santos, G.S., Šteinberga, I., 2023. Air pollution situation in small towns, including winter resorts: a comparative study of three cases in Northern Europe. Air Qual. Atmos. Health 16 (5), 945–961. https://doi.org/10.1007/s11869-023-01315-2.

Thiombane, M., Petrik, A., Di Bonito, M., Albanese, S., Zuzolo, D., Cicchella, D., et al., 2018. Status, sources and contamination levels of organochlorine pesticide residues in urban and agricultural areas: a preliminary review in central–Southern Italian soils. Environ. Sci. Pollut. Res. 25, 26361–26382. https://doi.org/10.1007/s11356-018-2688-5.

Tiwari, A., Kumar, P., Baldauf, R., Zhang, K.M., Pilla, F., Di Sabatino, S., Brattich, E., Pulvirenti, B., 2019. Considerations for evaluating Green infrastructure impacts in microscale and macroscale air pollution dispersion models. Sci. Total Environ. 672, 410–426. https://doi.org/10.1016/j.scitotenv.2019.03.350.

Ungaro, F., Maienza, A., Ugolini, F., Lanini, G., Baronti, S., Calzolari, C., 2022. Assessment of joint soil ecosystem services supply in urban Green spaces: a case study in Northern Italy. Urban For. Urban Green. 67, 127455. https://doi.org/10.1016/j.ufug.2021.127455.

Vannucchi, F., Scartazza, A., Macci, C., et al., 2025. Isotope signature and ecoenzymatic stoichiometry as key indicators of urban soil functionality. J. Soils Sediment. 25, 451–461. https://doi.org/10.1007/s11368-024-03892-w.

Venter, Z.S., Hassani, A., Stange, E., Schneider, P., Castell, N., 2024. Reassessing the role of urban Green space in air pollution control. Proc. Natl. Acad. Sci. 121 (6), e2306200121. https://doi.org/10.1073/pnas.2306200121.

Vigevani, I., Corsini, D., Mori, J., Pasquinelli, A., Gibin, M., Comin, S., Szwałko, P., Cagnolati, E., Ferrini, F., Fini, A., 2022. Particulate pollution capture by seventeen woody species growing in parks or along roads in two european cities. Sustainability 14 (3), 1113. https://doi.org/10.3390/su14031113.

Vitale, E., Napoletano, P., Colombo, C., et al., 2024. Use of compost to improve technosol properties and spontaneous plant-soil relationships of Mediterranean species potentially suitable for urban greening. Urban Ecosyst. 27, 1847–1861. https://doi.org/10.1007/s11252-024-01552-y.

Vos, P.E., Maiheu, B., Vankerkom, J., Janssen, S., 2013. Improving local air quality in cities: to tree or not to tree? Environ. Pollut. 183, 113–122. https://doi.org/10.1016/j.envpol.2012.10.021.

Wang, W., Dack, S., Mudway, I., Walder, H., Davies, B., Kamanyire, R., et al., 2023. Brownfield land and health: a systematic review of the literature. PLoS ONE 18 (8), e0289470. https://doi.org/10.1371/journal.pone.0289470.

WHO global air quality guidelines. 2021. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization. Licence: CC BY-NC-SA 3.0 IGO.

Yli-Pelkonen, V., Scott, A.A., Viippola, V., Setälä, H., 2017. Trees in urban parks and forests reduce O3, but not NO2 concentrations in Baltimore, MD, USA. Atmos. Environ. 167, 73–80. https://doi.org/10.1016/j.atmosenv.2017.08.020.

Yli-Pelkonen, V., Setälä, H., Viippola, V., 2017a. Urban forests near roads do not reduce gaseous air pollutant concentrations but have an impact on particles levels. Landsc. Urban Plan. 158, 39–47. https://doi.org/10.1016/j.landurbplan.2016.09.014.

Xu, X., Sun, Z., Hao, Z., Bian, Q., Wei, K., Wang, C., 2021. Effects of urban forest types and traits on soil organic carbon stock in Beijing. Forests 12 (4), 394. https://doi.org/10.3390/f12040394.

Zappitelli, I., Conte, A., Alivernini, A., Finardi, S., Fares, S., 2023. Species-Specific contribution to atmospheric carbon and pollutant removal: case studies in two Italian municipalities. Atmosphere 14 (2), 285. https://doi.org/10.3390/atmos14020285.

Zhao, H., Zheng, Y., Li, T., Wei, L., Guan, Q., 2018. Temporal and spatial variation in, and population exposure to, summertime Ground-Level ozone in Beijing. Int. J. Environ. Res. Public Health 15 (4), 628. https://doi.org/10.3390/ijerph15040628.