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Review

Ozone Pollution and Urban Greening

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Abstract

Tropospheric ozone (O_3) pollution is a major concern in urban environments because of its toxicity for both people and vegetation. This paper review provides an overview of atmospheric mechanisms, as well as the potential and best management practices of urban greening for reducing O_3 pollution in cities. Urban greening has often been proposed as a cost-effective solution to reduce O_3 pollution, but its effectiveness depends on careful species selection and integration with broader air quality management strategies. Ozone is a secondary pollutant and the volatile organic compounds emitted by vegetation (BVOCs) can play a prominent role in O_3 formation. A list of recommended and to-avoid species is given here to drive future planting at city scale. Planting low BVOC-emitting species and combining greening with reductions in anthropogenic emissions are key to maximizing benefits and minimizing unintended increases in O_3. Public and non-public institutions should carefully select plant species in consultation with expert scientists from the early stages, e.g., by considering local conditions and pollutant dynamics to design effective greening interventions. Collaborative planning among urban ecologists, atmospheric scientists, and municipalities is thus crucial to ensure that greening interventions contribute to overall air quality improvements rather than inadvertently enhancing O_3 formation. Such improvements will also translate into plant protection from O_3 stress. Therefore, future directions of research and policy integration to achieve healthier, O_3-resilient urban ecosystems are also provided.

Keywords: air pollution; green infrastructure; ground-level ozone; urban forest; BVOC emission; O_3 stress

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1. Introduction

Ground-level ozone (O_3) pollution, formed as a result of human activities emitting nitrogen oxides (NO_x) and volatile organic compounds (VOCs), is a growing global concern [1]. In recent decades, thanks to specific regulatory policies, the release of O_3 precursors has declined in Europe and North America whereas their emissions are increasing in East Asia, India, and lower geographical latitudes due to economic growth [2]. Ozone is a potent oxidant that causes significant stress to human health, biodiversity, ecosystems, and the climate. About 66% and 94% of the world population are exposed to excess O_3 for short-term and long-term exposure, respectively [3]. In cities, fine particles ($PM_{2.5}$), nitrogen dioxide (NO_2), and O_3 are the most harmful air pollutants in terms of adverse effects on human health [4–6]. In urban areas with more than 50,000 inhabitants worldwide, the annual mean $PM_{2.5}$ concentrations slightly declined from 2000 to 2019, while the annual NO_2 and O_3 mean concentrations increased [7]. In 2019, 37% of the 423,100 global deaths linked to O_3 pollution occurred in cities, which are home to 40% of the world population [5]. In addition, a fraction of O_3 can also infiltrate indoor environments leading to adverse health effects [8,9]. Thus, O_3 exposures must be urgently reduced to improve human health and ecosystem vitality. Furthermore, understanding the spatial and temporal dynamics of O_3, along with its precursors, is essential for designing efficient air quality management and mitigation strategies that combine regulatory policies and nature-based solutions, such as urban greening.

Urban greening mainly includes forested areas, public and private parks, street trees, botanical gardens, social allotments, green roofs, and green facades [10]. This urban green infrastructure ensures important environmental, social, and economic benefits for citizens [11]. The environmental benefits of urban greening are primarily related to stormwater mitigation, microclimate regulation, noise reduction, improved air quality, biodiversity enhancement, and carbon sequestration [12–15]. The presence of green recreational areas encourages citizens to be physically active, has a positive impact on cognitive performance and mental well-being, reducing anxiety and depressive symptoms [16,17]. Additionally, urban green spaces serve as meeting points where social interactions are enhanced, favoring community connections and integration [18]. Urban greening not only directly increases property values but also results in indirect income savings related to lower energy use due to the cooling effect on buildings [19]. Moreover, it can provide goods and products (e.g., timber) and create economic opportunities and jobs related to the green sector [20].

Urban greening is widely promoted as a strategy to improve air quality and reduce heat excess, but its impacts on O_3 pollution are complex [21]. While vegetation can remove O_3 from the air, it can also emit biogenic VOCs (BVOCs) that contribute to O_3 formation, especially in the presence of urban pollutants like NO_x [22–24]. Moreover, BVOCs are precursors of secondary organic aerosol pollution that has direct effects on O_3 formation by scattering light and changing photolysis rates [25]. Urban vegetation influences O_3 concentrations in complex ways that vary with time of day, meteorological conditions, season, and spatial configuration. These dynamics shape the net role of green spaces in O_3 mitigation and must be considered in urban planning. In addition, O_3 is toxic to plants when absorbed via their stomata.

This review paper aims to summarize the current knowledge about the mechanisms regulating O_3 pollution in urban environments, the potential of urban greening for reducing O_3 pollution in cities, and the most promising management options for urban greening to achieve O_3-free cities.

2. Mechanisms of Ozone Formation and Removal

Although a certain O_3 concentration in the troposphere is characteristic of background atmosphere, O_3 is recognized as a secondary pollutant formed through photochemical reactions involving NO_x and VOCs in the presence of sunlight. In a polluted atmosphere, O_3 formation is also stimulated by the oxidation of other air pollutants, e.g., methane and carbon monoxide. VOCs are emitted both from anthropogenic sources (AVOC), e.g., gasoline, and by biogenic sources, e.g., plants, known as BVOCs [26]. Many plant species emit high rates of BVOCs, which can react with NO_x to form O_3, especially during warm periods. The extent of this effect varies by species and environmental conditions [22,27–30]. Nevertheless, BVOCs (e.g., isoprene) can be consumed through ozonolysis although such reactions are generally considered scarce to deplete O_3 [31]. Interestingly, about 89% of total VOCs are emitted by vegetation at the global scale [32], thus, effectively contributing to surface O_3 formation. In detail, it was estimated that BVOCs exceed 1 PgC per year, approximately 10 times more than AVOCs [33].

Urban greening can directly remove O_3 from the air through dry or wet deposition on leaves [34,35] as well as uptake via the stomata [36]. Both mechanisms result in O_3 degradation. However, the O_3 that enters the leaves through the stomata also promotes the formation of oxidative products, i.e., reactive oxygen species, which are highly oxidative and generate a cascade of biochemical, physiological, and growth impacts on the plants that impair plant health [37].

To date, control strategies have focused more on NO_x than on VOCs, particularly in urban areas. Nonetheless, certain VOCs/NO_x ratios should be maintained by decreasing NO_x and/or VOCs as needed to reduce O_3 formation (Figure 1) [38,39]. In fact, a single decrease in NO_x reduces and increases O_3 production under "NO_x-limited" (e.g., in rural areas) and "VOCs-limited" (e.g., in cities) conditions, respectively. Moreover, the amount of O_3 produced not only depends on the VOCs/NO_x ratio but also on the VOCs composition, since isoprene has a stronger O_3 reactivity factor than other BVOCs, such as monoterpenes [40]. Among BVOCs, isoprene is also the most common compound (i.e., 70% of the total [41]) with a reactivity 22 times higher than important AVOCs, such as benzene [22]. Usually, the highest O_3 levels are recorded in peri-urban areas. However, a recent study reported that O_3 also increases in urban areas (on average + 0.31 ppb year^{-1}) since the 1990s [42]. Especially in Mediterranean cities, where solar radiation is more intense during summer, the VOCs/NO_x ratio can reach optimal values for O_3 production in the urban centers if high BVOC emitter trees are present. Therefore, selecting species and planting trees without accounting for the BVOC emission and O_3-formation potential could worsen O_3 pollution.

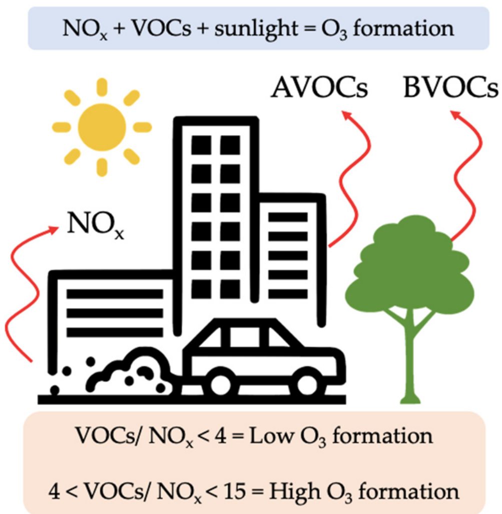

Figure 1. O_3 formation scheme and ratio between VOCs and NO_x according to Calfapietra et al. [36]. AVOCs and BVOCs refer to anthropogenic and biogenic emissions, respectively.

Being mainly generated through photochemical reactions, O_3 presents the highest values when the solar radiation is higher and the atmosphere is more reactive [43]. During the growing season, evergreen and deciduous tree species are extremely active and performant, especially during the springtime, when they have the highest gas exchange potential, with no or at least low water restriction, which promotes high stomatal conductance and thus high O_3 uptake. However, climate change increases the length of the growing season and could improve O_3 uptake [44] but also lead to higher overall potential O_3 damage to plants by reducing their absorption capacity. Therefore, the potential for vegetation to contribute to O_3 control is strongly seasonal. Furthermore, climate change induces extreme events during summer, such as heat waves and heavy drought periods, altering BVOC emissions, which depend on temperature and soil moisture, with a consequent impact on O_3 formation.

Ozone also exhibits an evident daily trend, with peak levels occurring in mid-afternoon, i.e., during the hours of higher solar irradiation and warmer temperature and drastically reducing during the night [43]. The vegetative gas exchange also follows a daily cycle. During the day, vegetation can significantly reduce surface-level O_3 through stomatal uptake as high solar radiation and temperature increase stomatal conductance, enhancing this removal process [45]. Although plants can absorb O_3 even at night [46], stomatal conductance drastically reduces the uptake not just of O_3 but of any other gaseous air pollutants, allowing concentrations to remain elevated or even increase due to reduced mixing at night.

3. Effectiveness and Limitations of Urban Greening

3.1. The Choice of Plant Species

The choice of plant species is critical to obtaining the maximum ecosystem benefits from urban greening. First, it should be kept in mind that species adapted to the characteristics of each environmental and climatic context are to be preferred for new planting initiatives [47]. It is preferable to choose native, not invasive, stress-tolerant, and low-allergenic species. Moreover, the ability to improve local air quality plays a relevant role [48]. For this reason, in recent decades, innovative models were developed to estimate the pollutant removal capacity of vegetation. Among them, iTree-Eco, AIRTREE, and FlorTree are open-source tools that have proven to be very helpful in identifying species with high air-amelioration potential [49–51].

Trees and shrubs with elevated O_3 removal capacity, due to high stomatal conductance values and low BVOC emissions (e.g., certain maples, lindens, hornbeams, and ash trees) are recommended to maximize benefits and minimize O_3 formation potential. Conversely, some species (especially certain oaks, willows, eucalypts, and poplars) release highly reactive BVOCs from their leaves (Table 1). Indeed, these species absorb less O_3 than they potentially produce and thus are not recommended for new plantings, especially in already polluted areas [52] even if they could represent an effective solution for allowing dry deposition of particulate matter (e.g., evergreen *Quercus* species with large canopies at maturity) and NO_2 absorption.

Table 1. Examples of recommended vs. to-avoid species according to their BVOC emissions.

Low-BVOC-Emitting Species	**High-BVOC-Emitting Species**
Lindens (*Tilia* × *europaea*; *Tilia cordata*; *Tilia platyphyllos*)	Oaks (*Quercus ilex*; *Quercus pubescens*; *Quercus petraea*)
Maples (*Acer campestre*; *Acer platanoides*; *Acer pseudoplatanus*)	Willows (*Salix alba*; *Salix babylonica*)
Hornbeams (*Ostrya carpinifolia*; *Carpinus betulus*)	Eucalypts (*Eucalyptus glaucescens*; *Eucalyptus globulus*)
Ash trees (*Fraxinus excelsior*; *Fraxinus angustifolia*)	Poplars (*Populus nigra*; *Populus alba*; *Populus tremula*)

Recently, evidence from a case study in Italy demonstrated how these processes translate into city-scale outcomes [53]. The mapping of urban vegetation revealed that large canopy areas dominated by high BVOC-emitting species might contribute to local O_3 formation rather than removal. In contrast, species associated with high stomatal uptake and low BVOC emissions were significantly correlated with lower O_3 concentrations. This example illustrates that the effectiveness of O_3 mitigation is strongly dependent on species selection and canopy distribution, confirming that urban greening can reduce ambient

O_3 levels when strategically managed. Thus, due to the tree sink-source balance, species with low O_3-forming potential (OFP) should be selected, while avoiding those with high OFP. For instance, at maturity, 1000 *Quercus ilex* trees planted in the Tuscany region of Italy would add about 30 tons of O_3 annually in the air, compared to about 150 tons if planting 1000 *Eucalyptus globulus* trees [51]. *Populus nigra* and *Liquidambar styraciflua* can also be planted in vast areas of the world, even in arid areas if irrigated, such as parks, gardens, and urban landscapes of the Middle East. However, planting 1000 trees of *P. nigra* would add 24.2 tons of $O_{3,}$ but this number would decrease to 11.2 tons of O_3 for 1000 *L. styraciflua* trees. Selecting species with low OFP could imply that the same result can be achieved with significantly fewer trees, thereby saving vast economic resources. Alternatively, planting the same number of trees with low OFP could also decrease O_3 exposures and related premature deaths.

3.2. The Choice of Plant Site and Nature-Based Solution

Air quality can also be affected by the right positioning of species in urban environments. For example, it should be considered that the presence of tree rows between tall buildings on both sides (i.e., street canyons) can have a marked influence and negative feedback on the transport of pollutants (e.g., NO_x), leading to a deterioration in local air quality. Several modelling studies demonstrated this phenomenon [21,54,55], showing higher net pollutant accumulations in street canyons below the tree canopies associated with increases in concentration, as especially observed on the leeward wall. However, design solutions, such as the use of mixed vegetation (trees-shrubs), can mitigate this negative effect and promote wind circulation [56].

Trees generally have a higher O_3 removal capacity than other Nature-based Solutions (NbS), with some species being particularly effective and cost-efficient for this purpose [22,46–48]. Green roofs represent an interesting NbS to effectively reduce tropospheric O_3 levels, although they show installation and maintenance costs that are approximately 10 times higher than those of trees [57]. Green roofs can be classified as extensive or intensive, depending on their composition and substrate depth [58,59]. The intensive green roofs include the presence of woody plants with greater maintenance requirements, while the extensive ones are the most common and are composed of only herbaceous species [60]. Turfgrass and succulent plant species (e.g., *Lolium*, *Festuca*, *Sedum*, *Thymus*, and *Heuchera* genera) are largely used to set up extensive green roofs, with stomatal uptake and dry deposition as the main O_3 removal pathways [61]. Moreover, green roofs can indirectly reduce O_3 concentrations by lowering building surface temperatures through evapotranspiration [62]. Indeed, lower air temperature decreases the photochemical reactions that lead to O_3 formation. Nonetheless, Baraldi et al. [63] found that some green roof species (i.e., herbaceous and shrubs) may also increase O_3 pollution in summer due to increased BVOC emissions.

4. Urban Planning and Management Considerations

4.1. Actions on the Urban Environment

Elevated CO_2 concentration, extreme heat, scarce precipitation, and pollution are limiting factors for stomatal conductance. Conversely, this parameter increases with higher rainfall and humidity as well as nitrogen deposition [64]. In addition, it is well recognized that stomatal conductance increases with rising mild temperature [65]; thus, if on one side deciduous species will mainly uptake O_3 but only during the warm growing season, in colder dormant months, they will lose foliage and show reduced physiological activity, lowering their capacity to absorb O_3. On the other hand, evergreen species will provide year-round O_3 removal; however, during the dormant season, besides the low

O_3 levels in the atmosphere, the plant physiological activity declines compared to peak summer performance.

Furthermore, the vegetation OFP also exhibits a seasonal trend, as BVOC emission is influenced by multiple factors, such as stomatal regulation, resource allocation, and environmental stress, emphasizing the complex mechanisms that drive BVOC production throughout the seasons [66]. For example, in response to water stress, plants close their stomata to reduce water loss [67], which also limits gas uptake. However, the effects of drought on BVOC emissions are diverse. While internal CO_2 reduction due to stomatal closure stimulates BVOC emissions, the decrease in emissions is expected to occur when severe drought stress occurs, with an expected recovery upon rewatering [68]. Additionally, the synthesis of terpenoids and isoprene is strongly affected by temperature and light, with emission peaks occurring between 25 °C and 30 °C but is inhibited at higher temperatures [69]. Tree maintenance, such as watering supply and pruning operations, plays an important role in improving air quality. In particular, heavy pruning intensity and frequency can strongly limit leaf biomass factors, directly involved in OFP, with repercussions both on O_3 uptake and BVOC emissions [70]. In addition, excessive pruning can induce severe physiological impairment to vegetation, and it is well documented that BVOC emissions increase during stress conditions [71].

Urban vegetation contributes to cleaner air by capturing particulate matter, absorbing gaseous pollutants, and lowering local temperatures through shading and evapotranspiration [72,73]. These cooling effects can, at the same time, reduce the atmospheric formation of O_3, which is temperature dependent. This complex chemical interplay means that urban greening alone is not always a guaranteed solution for better air quality.

In some contexts, especially where NO_x emissions remain high, increased BVOC emissions from large-scale greening initiatives can lead to higher O_3 concentrations, counteracting some of the intended benefits [38,74]. On the other hand, if NO_x levels are substantially reduced through targeted emissions control—such as cleaner transportation systems, industrial regulation, and energy transition—then the risk of O_3 formation from BVOCs diminishes [75].

4.2. Actions on the Urban Policy

The integration of traditional NO_x emission reduction strategies with urban greening represents a synergistic and effective approach to improving air quality in cities. Well-established technologies—such as the adoption of electric vehicles, the installation of Selective Catalytic Reduction systems in industrial facilities, and the implementation of Low Emission Zones—directly target primary sources of NO_x, thereby reducing pollutant concentrations at their source [75,76].

Although the advantages of urban trees were largely overlooked by policymakers until the past decade, city planners and decision-makers are key players in integrating urban green infrastructure tailored to local conditions. This should be done alongside emission reduction strategies and complementary interventions—such as cold air corridors and green roofs—to maximize health benefits and improve overall well-being. Such an integrated approach will also contribute to building more sustainable, climate-resilient cities over the long term [77].

The European Union launched the Biodiversity Strategy for 2030 (COM(2020)380) to protect nature and biodiversity and asked European municipalities with at least 20,000 inhabitants to develop "ambitious" Urban Greening Plans. By the end of 2030, under the Nature Restoration Law [78], Member States shall ensure that there is no net loss in the total national green spaces and tree canopy cover in urban ecosystem areas compared to 2024 and also ensure an increase after 2030. Following the EU recommendations, an intelligible guideline for urban greening, i.e., the "3-30-300 rule" was introduced in 2021 [79], allowing the establishment of efficient greening strategies. The 3-30-300 rule mandates that every citizen should see at least three mature trees from their home, live in neighborhoods with at least 30% tree canopy cover, and be within 300 m of a high-quality green space of at least 0.5 ha [79]. Citywide geospatial mapping and satellite-based approaches to assess the 3-30-300 rule compliance are instrumental in helping cities develop resilient and climate-neutral Urban Greening Plans [78] and offer a roadmap for identifying priority areas for greening or re-naturing in rapidly developing and densely populated cities. For instance, Aix-en-Provence (France) had 18% of buildings compliant with all three components, while Florence (Italy) had only 4% [80].

In 744 urban centers across Europe, Sicard et al. [77] demonstrated that each 5–point increase in tree canopy cover could reduce the annual $PM_{2.5}$ and NO_2 mean concentrations by 2.8% and 1.4%, and the summertime O_3 daily maximum 8 h concentrations by 1.2%, potentially preventing 4727 air pollution-related premature deaths each year. In addition, the mean tree canopy cover increased by 0.22% year^{-1} between 2000 and 2019 in the above urban centers. Reaching a mean tree cover of 30% in all investigated cities may be challenging or unattainable, particularly in dense built-up areas and densely populated cities or in cities facing water scarcity, but would result in a reduction in the number of premature deaths due to air pollution by 19.1 deaths per 10^5 people [77]. Tree planting programs need to target not only public spaces but especially private spaces such as residential yards, as well as peri-urban areas [81]. For instance, in Florence (Italy), 85% of trees are in private lands [82].

Based on the above considerations, Table 2 summarizes the recommendations for urban greening aimed at local stakeholders and city planners to effectively reduce O_3. These suggestions follow the findings of the AIRFRESH project (LIFE19 ENV/FR/000086) and have already been implemented in France by the municipalities of Aix-en-Provence and Nice.

Table 2. Recommendations for Urban Greening to maximize positive impacts on reducing O_3 in the air.

Recommendation	**Rationale**
Select low-BVOC, high O_3-removal species.	Reduce O_3 formation in the air and maximize O_3 removal by species.
Use green roofs to supplement trees.	Add pollutant removal capacity, especially where tree planting is limited.
Irrigate plants.	No drought stress reduces BVOC emissions and increases stomatal O_3 uptake.
In planting, consider the tree position.	Trees do not have to reduce ventilation in the city, e.g., do not plant tall trees along street canyons.
Avoid heavy pruning.	The lower the leaf biomass, the lower the O_3 uptake and BVOC emissions, but pruning stress stimulates BVOC emissions.
Maintain good plant health.	Plants under stress emit more BVOCs.
Cool the air.	O_3 formation increases with increasing temperature.
Incorporate into pollutant emission reduction policies.	Balances the effects of BVOC and NO_x on O_3 formation.
Respect the 3-30-300 rule.	Provide direct health benefits to the city inhabitants.
Target an average of 30% tree cover in a city.	Reduce the negative impacts of air pollution on human health.
Consider both private and public trees.	Support wise management of all urban green areas.
Tailor greening to local conditions.	Consider climate, pollution sources, and urban layout.

5. Conclusions

The role of urban vegetation in O_3 dynamics is not uniformly beneficial. The effectiveness of urban greening in mitigating O_3 pollution depends on many factors, among which the most important are the plant species, the local atmospheric conditions, and urban strategies. Effective greening strategies must account for these variables and should be guided by location-specific data and monitoring. Future directions of research should thus be devoted to improving our knowledge about species-specific O_3 net removal, how to use the urban forest to control local climate by reducing heat and promoting ventilation, using the urban green infrastructure as a field experiment to be monitored in the long term for the validation of present models, and finally supporting decision-makers in air-friendly green infrastructure planning and management.

The best species for O_3 net removal are usually large broadleaf trees with high stomatal conductance and low BVOC emissions, because they have elevated total leaf surface, high capacity for absorbing O_3 and reduced capacity of forming O_3 by the emitted BVOCs. Urban greening—through the expansion of trees, parks, green roofs, and other vegetation—has become an increasingly popular strategy for improving air quality in cities, but its effectiveness is highly dependent on how it is integrated with reductions in anthropogenic emissions, particularly nitrogen oxides. When properly coordinated, urban greening and emission control can produce substantial public health and environmental benefits. Yet, the relationship between the two is not straightforward and must be approached with care. Therefore, to achieve optimal air quality outcomes, urban greening must be implemented in tandem with strategic reductions in anthropogenic emissions. Indeed, only the effective coordination between conventional air pollution control policies and urban greening strategies permits cities to maximize public health benefits and long-term sustainability. Green space planning and air pollution control can jointly improve public health as well as reduce O_3 stress for vegetation. While the benefits of urban trees have been neglected by policymakers until the last decade, we encourage city planners and decision-makers to incorporate urban green infrastructure adapted to local settings in combination with emissions control strategies and other interventions (e.g., cold air corridor, green roofs) to maximize public health benefits and citizens' well-being, which would also result in more sustainable and climate-resilient cities in the long-term.

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