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Original article

FlorTree: A unifying modelling framework for estimating the species-specific pollution removal by individual trees and shrubs

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ABSTRACT

Atmospheric pollution is a threatening problem around the world, with tropospheric ozone (O_3), nitrogen dioxide (NO_2) and particulate matter (PM_{10}) among the most harmful pollutants for citizens' health. Nature-based solutions such as urban trees can cut down air concentrations of these pollutants thanks to stomatal uptake and dry deposition on their canopies and, in addition, uptake carbon dioxide (CO_2) and store carbon in their tissues. Unfortunately, some species emit biogenic Volatile Organic Compounds (bVOCs) that are O_3-precursors leading to air quality deterioration. As a proper selection of species is essential for urban greening, we developed an innovative single-tree model (FlorTree) to estimate the maximum flux of air pollutants. FlorTree considered species-specific parameters, such as tree morphology (height and crown leaf area), leaf/shoot structure, leaf habit (deciduous/evergreen) and eco-physiological responses to environmental factors, for 221 urban tree and shrub species. We applied the FlorTree model to examine i) which are the best species for air pollution removal in the case study of Florence (Italy) and ii) whether the species-specific removal performance is affected by different climate and air pollution conditions in other cities, namely Bucharest (Romania) and Tokyo (Japan). Results suggested that 24 tall trees (mainly broadleaves belonging to *Tilia*, *Acer* and *Fraxinus* genus) may be recommended for Florence due to their large crowns at maturity (50 years old), relatively high stomatal conductance and no bVOCs release. These general characteristics, however, were affected by climatic and pollutant conditions, suggesting that FlorTree must be applied to the local conditions. Therefore, our results demonstrated that FlorTree can be applied in any city for maximizing the air quality improvement by urban trees.

1. Introduction

The world population is increasingly concentrating in the urban environment. At present, more than half of the world population lives in urban areas (30% more than in 1950), a proportion that is expected to increase to 68% by 2050 (United Nations, 2022). Currently, air pollution is one of the main problems affecting urban areas and will become even more pressing with the population growth. Air pollutants, in fact, arise from anthropogenic emissions, mainly linked to vehicular traffic, industry, power stations, trade and domestic fuel (Manisalidis et al., 2020). Among the atmospheric pollutants, tropospheric ozone (O_3), nitrogen dioxide (NO_2) and particulate matter (PM) are the most dangerous and harmful because they can cause negative effects on human health by inducing respiratory and cardiovascular diseases (Anenberg et al., 2022; Malashock et al., 2022; Southerland et al., 2022; Sicard et al., 2023). Despite significant progress, Sicard et al. (2021)

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found that urban exposure to fine PM and O_3 of European citizens still exceeded the World Health Organization (WHO) limit values in 2017, suggesting that intensified actions are urgently needed.

The scientific community agrees that nature-based solutions (NBS) such as planting tree species in the urban environment represent an ecological strategy to improve city air quality (Nowak, 2002; Hewitt et al., 2019). In fact, trees work as biological filters, uptaking gaseous air pollutants from the city atmosphere by leaf stomata and plant surfaces, and removing PM by intercepting airborne particles with their canopies (Nowak et al., 2006, Samson et al., 2017). Moreover, urban greening increases recreational, psychological, social, and aesthetic benefits for the community (Ugolini et al., 2020) and also has an effective and important role in climate change mitigation and adaptation as plants absorb and sequester CO_2 and reduce the effect of extreme events (Samson et al., 2019).

Interestingly, tree species have different capabilities of removing atmospheric pollutants and of emitting biogenic volatile organic compounds (bVOCs) that are precursors of O_3, secondary organic aerosols and particulate matter (Laothawornkitkul et al., 2009). Usually, the positive effects on air quality are maximised by plants with high canopy density, longevity of the foliage, drought and disease resistance and low emission of bVOCs (Grote et al., 2016; Barwise and Kumar, 2020). Therefore, the selection of suitable species for green infrastructures is a crucial step for a correct urban planning (Sicard et al., 2022). Several modelling approaches have been developed over the years to assess the magnitude of air pollution removal by trees and other types of NBS. One of the most used models in urban and peri-urban environments is i-Tree Eco dry deposition model (developed from the Urban Forest Effects (UFORE) model, utilizing its dry deposition component (UFORE-D) to simulate pollution removal to trees and shrubs from the atmosphere during non-precipitation period), that employs field-surveyed urban forest information, location specific data, weather data, and air pollutant measurements, to assess and quantify the environmental services that trees provide (Hirabayashi et al., 2012). Bottalico et al. (2017) suggested a different approach where field surveys were integrated with LiDAR data to provide a methodological framework for mapping the air pollutant removal by urban forests, while Fares et al. (2019) proposed a multi-layer model (AIRTREE) to predict CO_2, water, O_3, and PM exchanges between leaves and the atmosphere in a Mediterranean Holm oak forest. Conversely, a single tree model was developed by Pace et al. (2020) to simulate cooling, shading and O_3 absorption of an urban tree (*Tilia cordata*). However, previous studies considered only land cover and plant types (C_3 trees, Hirabayashi et al., 2011) or single tree species while the species selection requires more extensive species-specific information on physiological and morphological characteristics relating to pollutant removal capacities (Baraldi et al., 2019).

Local climate and pollutant conditions may be another important factor to affect air pollution removals by trees (Schaubroeck et al., 2014; Vigevani et al., 2022). In fact, hot and dry summer induces an increase in air humidity deficit, causing stomatal closure and thus limiting leaf gas exchange (Larcher, 2003). At the same time, high temperature increases the emission of bVOCs, stimulating O_3 formation in the atmosphere (Calfapietra et al., 2013). Considering the species-specific difference in stomatal characteristics and bVOCs emission rate, we hypothesized that the optimal tree species may be different among cities according to the different local climate and pollutant conditions. However, to the best of our knowledge, city-to-city comparison studies for the urban species selection are scarce (Cushing, 2009).

Aim of this paper was to develop a new unifying modelling framework (FlorTree) for assessing the species-specific balance of O_3 (by summing up potential O_3 formation based on emission of bVOCs, and surface and stomatal deposition of O_3), the total removal of NO_2, the deposition of PM_{10}, and the uptake and storage of CO_2 for mature woody plant individuals grown in healthy and isolate conditions. This modelling approach was firstly applied to a case study in Florence (Italy) and allowed to categorise more than 200 species (trees and shrubs) based on their air pollution improvement capacity. Furthermore, we performed a sensitivity analysis by applying FlorTree to 15 species common to other urban contexts (Bucharest, Romania and Tokyo, Japan) with different meteorological and pollution conditions.

2. Materials and methods

2.1. Selection of the plant species

The list of species was defined by comparing the information collected by major municipalities of Tuscany in central Italy, i.e., Florence, Lucca, Pistoia, and Prato. It includes the tall trees (height > 10 m), small trees (3 m $<$ height < 10 m) and shrubs (height < 3 m) commonly used in these urban environments. In total our final list counted 221 plant species subdivided in 116 tall trees, 60 small trees and 45 shrubs. We then used inaturalist (https://www.inaturalist.org) to detect the species that occur both in Florence than Bucharest, and Tokyo. We selected 15 common urban tree species and applied FlorTree to assess removal pollutant capabilities (O_3, NO_2 and PM_{10}) in different climatic environments. According to Koppen classification (Peel et al., 2007), Florence, Bucharest and Tokyo belong to three different climates: Mediterranean (Csa), Continental (Dfa) and Humid subtropical (Cfa), respectively.

2.2. Air pollution and meteorological data

The period examined was from 30/6/2017–30/6/2018, as one year covers the growing season of all species. Concerning Florence, meteorological data were collected by a station located at CNR LaMMA / IBE, 43°50′56" N - 11°09′04" E – 45 m a.s.l. Air temperature (T) and relative humidity (RH) were measured at 5 m above the ground thanks to a thermohygrometer (Vaisala), and wind speed and direction were obtained at 20 m with an ultrasonic anemometer (Gill windsonic). Global radiation (G) was recorded by a radiometer (Kipp&Zonen) placed 16 m above the ground. Hourly air pollutant concentrations were recorded at the stations Gramsci (NO_2, PM_{10}) and Settignano (O_3), situated in the city of Florence, by the Tuscany Region Environmental Protection Agency (ARPAT). Regarding Bucharest (Romania) and Tokyo (Japan), air pollutant and meteorological data were available from monitoring stations belonging to the National Agency for Environmental Protection (ANPM) and the Atmospheric Environmental Regional Observation System (AEROS), respectively. In particular, hourly concentrations refer to a station located in the city center of Bucharest (44°26′50" N - 26°02′12" E – 91 m a.s.l.) while in Tokyo air pollutants were measured in Shinjuku (NO_2, PM_{10}) and Nishi-Tokyo (O_3). Moreover, as in Japan suspended particulate matter (SPM) is monitored, we used this conversion factor for PM_{10} ($=$ SPM $\times$ 1.07, Koyama and Kishimoto, 2001).

2.3. Removal of air pollutants

A simplified formula was applied to estimate the flux of air pollutants (F_{tree}, g tree^{-1} s^{-1}) to individual trees (Omasa et al., 2002; Nowak et al., 2006; Bottalico et al., 2017).

$$F_{\text{tree}} = \text{LA} \times F_{\text{leaf}} \tag{1}$$

$$F_{\text{leaf}} = (1-R) \times V_{\text{d}} \times C \tag{2}$$

where F_{leaf} is the flux of air pollutants removed per unit leaf area (g m^{-2} s^{-1}), LA is leaf area of an individual tree (m^2). LA was estimated by multiplying leaf area index (LAI, m^2 m^{-2}) by crown area (m^2) (Nock et al., 2008). Species-specific crown area data were obtained from nursery catalogs (Innocenti & Mangoni piante Catalogo, 2022; Vannucci piante Catalogo, 2022) and LAI values were obtained from a global database of field-observed LAI in woody plant species (Iio and Ito, 2014). R is the resuspension rate ($R = 0$ for O_3 and NO_2, Omasa et al., 2002; $R = 0.5$ for PM_{10}, Zinke, 1967), V_{d} is the deposition velocity for each pollutant (m s^{-1}) and C is the concentration of target air pollutants at height z (expressed in μg m^{-3}). V_d can be given as:

$$V_d = 1 \,/\, (r_a + r_b + r_c) \tag{3}$$

where r_a is the aerodynamic resistance (s m^{-1}), r_b is the quasi-laminar boundary layer resistance (s m^{-1}) and r_c is the bulk surface resistance (s m^{-1}). The aerodynamic resistance (r_a) was estimated by the following equation assuming the neutral atmospheric stability condition (Erisman et al., 1994):

$$r_a = 1/(k \cdot u^*) \cdot \log\{(z - d)/z_0\} \tag{4}$$

where k is the von Karman constant (0.4), u^* is the friction velocity (m s^{-1}), z_0 is the roughness length ($0.1 \cdot h$, m; h is the tree height), d is the zero-plane displacement ($0.7 \cdot h$, m). The other resistances (r_b and r_c) to the transfer of gas pollutants (O_3 and NO_2) and PM_{10} are described in the following Sections 2.3.1 and 2.3.2.

2.3.1. Ozone and nitrogen dioxide

The quasi-laminar boundary layer resistance (r_b) to gas pollutant transfer was calculated by the empirical equation suggested by Hicks et al. (1987). It is given by:

$$r_b = 2/(k \cdot u^*) \cdot (\mathrm{Sc}/\mathrm{Pr})^{2/3} \tag{5}$$

where Sc is the Schmidt number (1.07 for O_3 and NO_2) and Pr is the Prandtl number (0.72).

The bulk surface resistance (r_c) to gas pollutant transfer was estimated as:

$$r_c = 1 \,/\, (g_s / [D_{H2O}/D_{gas}] + g_{ext}) \tag{6}$$

where g_s is the stomatal conductance for water vapour and g_{ext} is the external leaf or cuticular conductance. g_{ext} was set to 0.005 m s^{-1} according to Wesely (1989). D_{H2O}/D_{gas} accounts for the difference in diffusivity of water and target gas pollutant (1.6 for O_3 and NO_2, Wesely, 1989).

Leaf-level stomatal conductance was estimated by a simple multiplicative algorithm (Jarvis, 1976; Hoshika et al., 2020). The model equation is given as:

$$g_s = g_{max} \cdot f_{light} \cdot \max\{f_{min}, (f_{temp} \cdot f_{VPD})\} \tag{7}$$

where g_{max} is the species-specific maximum stomatal conductance and f_{min} is the minimum stomatal conductance. To simplify the calculation, we assumed that f_{min} was zero (Felzer et al., 2004). The functions f_{light}, f_{temp} and f_{VPD} depend on solar radiation (G, W m^{-2}), air temperature (T, °C), and vapor pressure deficit (VPD, kPa), respectively, and are scaled from 0 to 1. To parametrize the species-specific g_{max}, a literature survey was carried out to collect the g_{max} data (Supplementary Table S1). Using Scopus and Google scholar, a survey of all peer-reviewed literature published between 1970 and 2018 was made on the basis of the keywords "[stomatal conductance] + [a target species name]", including studies under natural environmental conditions and manipulative experiments.

According to Wesely (1989) and Zhang et al. (2003), stomatal responses to light (f_{light}) and temperature (f_{temp}) were described by the following general formulas:

$$f_{light} = 1/[1 + \{200 \cdot (G + 0{\cdot}1)^{-1}\}^2] \tag{8}$$

$$f_{temp} = \left(\frac{T - T_{min}}{T_{opt} - T_{min}}\right) \left\{ \left(\frac{T_{max} - T}{T_{max} - T_{opt}}\right)^{\left(\frac{T_{max} - T_{opt}}{T_{opt} - T_{min}}\right)} \right\} \tag{9}$$

where G is solar radiation (W m^{-2}), T is air temperature (°C) while T_{max}, T_{min} and T_{opt} were set to 40, 0 and 25 °C, respectively (Hoshika et al., 2018).

The response of stomatal conductance to VPD (f_{VPD}) was described by a logarithmic function (Oren et al., 1999; Büker et al., 2015):

$$f_{VPD} = 1 - m \cdot \ln\,[\mathrm{VPD}] \tag{10}$$

where m denotes the sensitivity of stomatal conductance to VPD (ln $(kPa)^{-1}$). According to a review by Hoshika et al. (2018), we set m to 0.6.

2.3.2. PM_{10}

To calculate the PM_{10} removal by trees, Tiwary et al. (2009) applied a pollution flux approach based on species-specific deposition velocities. According to their study, the r_b to the transfer of PM_{10} was calculated as:

$$r_b = B^{-1} \cdot (u^*)^{-1} \tag{11}$$

where $B^{-1} = 2 \cdot (2\, u^*)^{-1/3}$ according to Killus et al. (1984).

The bulk surface resistance (r_c) to the transfer of PM_{10} was calculated as:

$$r_c = 1/V_{g(s)} - (r_a + r_b) \tag{12}$$

where $V_{g(s)}$ is the PM_{10} deposition velocity value for each plant species per unit leaf area (m s^{-1}). The relationships between wind speed and $V_{g(s)}$ for various conifer and broadleaved tree species were reported by Beckett et al. (2000) and Freer-Smith et al. (2004). According to these published data, we developed a simple empirical model:

$$V_{g(s)} = a \cdot \exp[b \cdot (\mathrm{U} - 3)] \tag{13}$$

where U is wind speed (m s^{-1}), a is a species-specific $V_{g(s)}$ at 3 m s^{-1} of wind speed, b is an empirical coefficient determining a curvature of the relationship between $V_{g(s)}$ and U. As shoot/leaf structure may affect the particle deposition for plants (Katata and Nagai, 2010; Räsänen et al., 2013), we applied a multiple linear regression analysis to characterise the species-specific parameters a and b by using several leaf/shoot morphological parameters (Table 1). Species-specific parameters for the target leaf/shoot morphology were obtained from the literature survey and the LEDA Traitbase developed by the University of Oldenburg (Kleyer et al., 2008) (Table S2).

To select the best model, we compared the AIC (Akaike's Information Criterion) for the performance of the model with different combinations of parameters. As a result, we obtained the following equations:

$$a = 1{\cdot}5007 - 3{\cdot}1924 \times \mathrm{STAR} + 0{\cdot}1578 \times \mathrm{PT},$$

$$b = 0{\cdot}30821 - 0{\cdot}2961 \times \mathrm{STAR} + 0{\cdot}07154 \times \mathrm{PT} \tag{14}$$

where STAR is shoot silhouette to total leaf area ratio (0–0.5), and PT is phyllotaxis (1: opposite, 2: spiral, 3: fascicled, 4: decussated).

2.3.3. Ozone Forming Potential (OFP) and net ozone uptake

The ozone-forming potential (g $plant^{-1} day^{-1}$) was calculated according to the formula and method by Benjamin and Winer (1998):

$$\mathrm{OFP} = \mathrm{B}[(\mathrm{E}_{iso}\mathrm{R}_{iso}) + (\mathrm{E}_{mono}\mathrm{R}_{mono})] \tag{15}$$

where B [(kg leaf) $tree^{-1}$] is dry-biomass for a target species calculated by multiplying species-specific leaf mass per area (LMA, kg m^{-2}) extracted from Kleyer et al. (2008) (Supplementary Table S3), by leaf area of individual tree (LA, m^2). Since bVOC emissions are light, temperature and water availability-dependent (Owen et al., 2002; Feldner et al., 2022), emission rates of isoprene (E_{iso}) and monoterpene (E_{mono})

Table 1
Tested leaf/shoot parameters for the multiple linear regression analysis.

Tested parameter	Abbreviation
STAR (Shoot silhouette to total leaf area ratio)	STAR
Leaf size	LS
Presence of leaf hairness	TR
Phyllotaxis	PT
Specific leaf area	SLA

were calculated thanks to the following algorithms proposed by Guenther et al., (1995):

$$E_{iso} = E_s C_T C_L \tag{16}$$

$$E_{mono} = \exp(\beta\,(T - T_s))\,M_{Ts} \tag{17}$$

where E_s and M_{Ts} are species-specific mass emission rate [(μg bVOC) (g leaf dry weight)$^{-1}$ h^{-1}], C_T and C_L are constants depending on temperature and light, respectively, β is an empirical coefficient and $T_s = 30$ °C. Species-specific mass emission rates of isoprene (E_s) and monoterpene (M_{Ts}) were extracted by a database of Lancaster University (Hewitt et al., 1997) and scientific literature (Table S4).

Instead, R_{iso} and R_{mono} are reactivity factors [(g O_3) (g bVOC)$^{-1}$] equal to 9.1 for isoprene and 3.8 for monoterpenes considering the Maximum Incremental Reactivity scale (MIRs) provided by Carter (1994). Finally, for each plant species, we calculated the net O_3 uptake (g plant^{-1}day^{-1}) using the following simple formula:

$$\text{Net } O_3 \text{ uptake} = O_3 \text{ removal} - \text{OFP} \tag{18}$$

where "O_3 removal" is equal to F_{tree} considering O_3 concentrations (Eqs. (1) and (2)).

2.3.4. CO_2 storage and sequestration

The total carbon stored by a single plant species was determined by multiplying dry weight tree biomass (DWB) by a conversion coefficient of 0.50, and then by 3.67 to convert carbon into CO_2 (McPherson and Simpson, 1999).

DWB of an individual tree or shrub was calculated based on the estimation of plant volume with the equation developed by Wu (2019):

$$DWB_i = d \cdot t \cdot \rho_i \cdot V_i \tag{19}$$

where V_i (m^3) is the stem volume; ρ_i (kg·m^{-3}) is the species-specific wood density; t (1.28) is the total biomass conversion factor to include belowground biomass based on the average root-to-shoot ratio; d is a constant to convert fresh weight to dry weight and it is 0.48 for evergreen species and 0.56 for deciduous species. To establish the species-specific ρ_i we used the values included in the global wood density database (Zanne et al., 2009) referring to European region.

To calculate the individual stem volume, we used the following allometric formula proposed by Burkhart and Tomé (2012):

$$V_i = b_0 + b_1 (\text{DBH})^2\, h \tag{20}$$

The coefficients b_0 and b_1 were set to 0.00626 and 0.00003666, respectively, as proposed by Burkhart (1977). DBH is the stem diameter at breast height, while h is the plant height; these species-specific values were found in the Urban Trees Database (McPherson et al., 2016). For each species, V_i was calculated with DBH and h values measured across a range of plant ages.

With this approach, we calculated CO_2 storage according for 61 street tree species present in the Urban Trees Database. For each individual species, annual CO_2 sequestration was obtained as CO_2 storage/tree age. Finally, a linear regression between tree age and CO_2 sequestration was estimated allowing to determine CO_2 sequestration for 50-year-old trees (CO_2 seq 50) for each species as a reference tree age.

When data were insufficient to calculate the CO_2 seq 50 for a certain species, the average value from the same genus or family was used. If no genus or family CO_2 seq 50 was available, the average values from all trees (T) or shrubs (S) were used.

2.4. Species ranking

For each species, a score was assigned to synthesise their ability to remove air pollutants. The ranking was obtained starting from the database and calculating the average removal or abatement value for each pollutant. A score of 0, 1, 2, 3 was assigned when values were ≤ the 25th percentile, between 25th and 50th percentile, between 50th and 75th percentile, ≥ 75th percentile, respectively (Sicard et al., 2018). The final species ranking was obtained by summing up the individual scores for each pollutant, so that a score > 10 means elevated removal ability and a score < 3 means low ability. Moreover, the adaptation to the local climate of these species was considered taking into account specific ecological indices (temperature and continentality) suggested by Ellenberg (1974). In particular, we considered Temperature and Continentality of Florence to assess the species adaptable to the climatic conditions present in those urban environments.

3. Results

In Tables 2, 3, 4 and 5, a list of the 10 best and worst species divided by each type of pollutant (NO_2, O_3, PM_{10} and CO_2) is presented. Moreover, the best trees to plant in Florence, according to our pollutant-removal scoring and climate resilience, are shown in Table 6. Finally, a comparison between removal ability of O_3, NO_2 and PM_{10} by 15 common tree species in Florence, Bucharest and Tokyo is shown in Figs. 1, 2 and 3.

3.1. Gaseous pollutant (NO_2 and O_3) removal

Large conifers such as *Pseudotsuga menziesii* (31.31 g tree^{-1}day^{-1}) and *Cedrus libani* (22.10 g tree^{-1}day^{-1}) showed high removal capacity for NO_2 (Table 2), followed by broadleaf species of the genera *Fraxinus*, *Fagus*, *Liriodendron*, *Tilia*, *Quercus*, *Platanus* and *Eucalyptus*. Among them, *Fraxinus excelsior* and *Fagus sylvatica* showed the best performance with more than 19 g tree^{-1} of NO_2 removed daily from the air. The lowest performance (≤ 0.008 g of NO_2 day^{-1}) was recorded for shrubs belonging to the following genera: *Rubus*, *Lavandula*, *Hypericum*, *Ruscus* and *Erica*. In particular, *Erica multiflora* showed a daily removal of just 0.0006 g tree^{-1}.

Fraxinus excelsior (26.05 g tree^{-1}day^{-1}) and *Fagus sylvatica* (24.76 g tree^{-1}day^{-1}) had a strong capability to remove O_3 and were characterised by a low OFP. Also *Tilia platyphyllos* (23.42 g tree^{-1}day^{-1}), *Tilia cordata* (22.48 g tree^{-1}day^{-1}), *Tilia x europaea* (17.35 g tree^{-1}day^{-1}) as well as *Aesculus hippocastanum* (13.20 g tree^{-1}day^{-1}) showed high net O_3 uptake thanks to their OFP equal to zero. OFP of *Liriodendron tulipifera* and *Cedrus libani* was not negligible (9.67 and 7.54 g tree^{-1}day^{-1} respectively) and their net O_3 uptake was 15.39 and 16.20 g tree^{-1}day^{-1} despite high values of O_3 removal (Annex 1). Conversely, *Quercus*, *Populus*, and *Eucalyptus* species showed high values of OFP and thus a negative balance for net O_3 uptake. In particular, *Eucalyptus globulus*

Table 2
Best/worst 10 species for NO_2 removal (in g tree^{-1}day^{-1}, average annual value).

	Genus	Species	NO_2 removal
Best	*Pseudotsuga*	*menziesii*	31.31
	Cedrus	*libani*	22.10
	Fraxinus	*excelsior*	19.45
	Fagus	*sylvatica*	19.37
	Liriodendron	*tulipifera*	18.84
	Tilia	*platyphyllos*	17.61
	Quercus	*ilex*	17.61
	Tilia	*cordata*	16.76
	Platanus	*x acerifolia*	16.67
	Eucalyptus	*globulus*	16.04
Worst	*Rubus*	*occidentalis*	0.0080
	Rubus	*ulmifolius*	0.0080
	Rubus	*ursinus*	0.0080
	Rubus	*fruticosus*	0.0079
	Lavandula	*luisieri*	0.0079
	Hypericum	*perforatum*	0.0078
	Lavandula	*stoechas*	0.0078
	Ruscus	*aculeatus*	0.0034
	Erica	*arborea*	0.0019
	Erica	*multiflora*	0.0006

Table 3 -
Best/worst 10 species for net O_3 uptake (in g tree^{-1}day^{-1}, average annual value), i.e., O_3 removal minus Ozone Forming Potential (OFP).

	Genus	Species	O_3 removal	OFP	Net O_3
Best	*Fraxinus*	*excelsior*	26.05	0.00	26.05
	Fagus	*sylvatica*	25.88	1.12	24.76
	Tilia	*platyphyllos*	23.42	0.00	23.42
	Tilia	*cordata*	22.48	0.00	22.48
	Acer	*platanoides*	17.79	0.10	17.69
	Tilia	*x europaea*	17.35	0.00	17.35
	Acer	*pseudoplatanus*	18.12	1.03	17.09
	Cedrus	*libani*	23.74	7.54	16.20
	Liriodendron	*tulipifera*	25.07	9.67	15.39
	Aesculus	*hippocastanum*	13.20	0.00	13.20
Worst	*Liquidambar*	*styraciflua*	8.08	63.58	-55.50
	Quercus	*petraea*	18.41	85.89	-67.49
	Quercus	*suber*	11.11	79.14	-68.03
	Quercus	*ilex*	19.02	103.53	-84.51
	Populus	*nigra*	10.27	125.73	-115.46
	Eucalyptus	*glaucescens*	3.89	128.51	-124.62
	Quercus	*robur*	13.79	138.58	-124.79
	Quercus	*frainetto*	5.13	184.37	-179.24
	Quercus	*coccinea*	9.31	243.10	-233.79
	Eucalyptus	*globulus*	17.43	428.93	-411.49

Table 5 -
Best/worst 10 species considering CO_2 storage (in t plant^{-1}) and sequestration (in kg plant^{-1}year$^{-1)}$.

	Genus	Species	CO_2 storage	CO_2 sequestration
Best	*Eucalyptus*	*viminalis*	5.57	111.46
	Eucalyptus	*globulus*	5.57	111.46
	Eucalyptus	*camaldulensis*	5.57	111.46
	Eucalyptus	*glaucescens*	5.57	111.46
	Quercus	*palustris*	5.38	107.68
	Fagus	*sylvatica*	5.01	100.14
	Acer	*negundo*	4.85	96.90
	Pinus	*canariensis*	4.42	88.47
	Betula	*nigra*	4.40	88.00
	Castanea	*sativa*	4.17	83.40
Worst	*Myrtus*	*communis*	0.95	19.00
	Callistemon	*citrinus*	0.95	19.00
	Malus	*communis*	0.76	15.26
	Picea	*pungens*	0.76	15.19
	Prunus	*cerasifera*	0.69	13.87
	Pinus	*sylvestris*	0.64	12.83
	Pyrus	*communis*	0.60	12.04
	Olea	*europaea*	0.55	11.05
	Acer	*japonicum*	0.46	9.22
	Lagerstroemia	*indica*	0.40	7.92

Table 4
Best/worst 10 species for PM_{10} deposition (in g tree^{-1}day^{-1}, average annual value).

	Genus	Species	PM_{10} deposition
Best	*Pseudotsuga*	*menziesii*	12.63
	Cedrus	*libani*	9.56
	Picea	*abies*	6.31
	Fagus	*sylvatica*	4.80
	Cedrus	*atlantica*	4.13
	Quercus	*ilex*	3.13
	Quercus	*rotundifolia*	2.73
	Pinus	*pinea*	2.46
	Quercus	*rubra*	2.17
	Quercus	*petraea*	2.16
Worst	*Cistus*	*incanus*	0.0008
	Hypericum	*perforatum*	0.0007
	Cytisus	*battandieri*	0.0005
	Cytisus	*multiflorus*	0.0005
	Cytisus	*praecox*	0.0005
	Cytisus	*scoparius*	0.0005
	Ruscus	*aculeatus*	0.0005
	Erica	*multiflora*	0.0003
	Lavandula	*luisieri*	0.0003
	Lavandula	*stoechas*	0.0003

produces significant daily quantities of O_3 (428.93 g tree^{-1}) inducing a negative gap in the net O_3 uptake (−411.49 g tree^{-1}day^{-1}). *Q. petraea* and *Q. ilex* showed an O_3 removal capacity similar to *Tilia x europaea, A. pseudoplatanus* and *A. platanoides* but their high values of OFP resulted in a negative O_3 balance equal to – 67.49 g tree^{-1}day^{-1} and – 84.51 g tree^{-1}day^{-1}, respectively.

3.2. PM_{10} deposition

Conifers showed the best results for PM_{10} removal (Table 4). *Pseudotsuga menziesii* showed the highest value of deposition (12.63 g tree^{-1}day^{-1}) followed by *Cedrus libani* (9.56 g tree^{-1}day^{-1}) and *Picea abies* (6.31 g tree^{-1}day^{-1}). Also the conifer *Cedrus atlantica* and *Pinus pinea* were in the group of best ten species with a PM_{10} removal capacity of 4.13 and 2.46 g tree^{-1}day^{-1}, respectively. Also broadleaf species i.e. *Fagus sylvatica* (4.80 g tree^{-1}day^{-1}) and *Quercus* species (2.16 – 3.13 g tree^{-1}day^{-1}) showed high daily capacity to remove PM_{10} from the atmosphere. Among them, the evergreen oak *Q. ilex* showed better results than the deciduous oaks. Instead, shrubs belonging to *Cistus*, *Hypericum, Cytisus*, *Ruscus*, *Erica,* and *Lavandula* genera showed the worst performances, and the lowest value was recorded for *Lavandula stoechas* with a deposition of PM_{10} equal to 0.0003 g tree^{-1} day^{-1}.

3.3. CO_2 storage and sequestration

The highest CO_2 storage and sequestration was found for tall trees, while the lowest was found for shrubs and small trees (Table 5). *Eucalyptus* species stored the greatest amount of CO_2 removing 111.46 kg from the atmosphere annually. *Quercus palustris* and *Fagus sylvatica* also removed more than 100 kg year^{-1} of CO_2 storing in their tissues 5.01 and 5.38 tons of this greenhouse gas at maturity, respectively. Among conifers, only *Pinus canariensis* was in the top ten species uptaking 88.47 kg year^{-1} of CO_2. Small trees with a "shrub-like" habit such as *Lagerstroemia indica* and *Acer japonicum* showed the lowest values of CO_2 storage and sequestration removing from the air less than 10 kg year^{-1}. However, also fruit trees such as *Malus communis*, *Pyrus communis*, *Prunus cerasifera* and *Olea europaea* showed low CO_2 sequestration with values ranging from 11 to 15 kg plant^{-1}year^{-1}.

3.4. Total score

According to our ranking (Table 6), the following eight species achieved the maximum score: *Tilia plathyphillos*, *Tilia x europaea*, *Tilia cordata*, *Acer negundo*, *Acer pseudoplatanus Acer platanoides Quercus cerris* and *Quercus palustris*. However, also *Fagus sylvatica* and *Pseudotsuga menziesii* achieved 12 points but they were excluded from the list as they are not well adapted to the local climate of Florence. Moreover, 16 species reached a score of 11. Among them, 12 were deciduous trees (*Fraxinus excelsior*, *Fraxinus angustifolia, Fraxinus uhdei*, *Fraxinus velutina*, *Aesculus hippocastanum*, *Carpinus betulus, Ostrya carpinifolia, Juglans regia, Zelkova serrata, Ulmus americana, Platanus x acerifolia* and *Liriodendron tulipifera*) and four were conifers (*Cedrus libani*, *Cedrus atlantica*, *Cedrus deodara* and *Taxus baccata*). Ash species, *A. hippocastanum*, *C. betulus*, *O. carpinifolia*, *Zelkova serrata* and *J. regia* showed a lower score (2 instead of 3) than *Cedrus* species for PM_{10} deposition but this was offset by reaching the highest scoring for CO_2 storage and sequestration. *U. americana*, *Platanus x acerifolia* and *L. tulipifera* achieved maximum score both for O_3, NO_2 and PM_{10} while recorded 2 points for CO_2 sequestration. On the contrary, *T. baccata* got 2 points for NO_2 removal but top score for the other pollutants.

Despite *Abies alba, Picea abies, Alnus glutinosa* and *Pinus radiata* reached 11 points, they were not considered in the list as their ecology is not well adapted to the local climate.

Table 6 –
Best species for planting in Florence according to our ranking (score > 10). The total score was obtained by summing the individual scores for each pollutant. *Fagus sylvatica*, *Pseudotsuga menziesii*, *Abies alba*, *Picea abies*, *Alnus glutinosa* and *Pinus radiata* were removed from the table because they are not well suited to be planted in Florence due to their ecology.

Genus	Species	Net O_3	NO_2	PM_{10}	CO_2	Score
Tilia	*platyphyllos*	3	3	3	3	12
Tilia	*x europaea*	3	3	3	3	12
Tilia	*cordata*	3	3	3	3	12
Acer	*negundo*	3	3	3	3	12
Acer	*platanoides*	3	3	3	3	12
Acer	*pseudoplatanus*	3	3	3	3	12
Quercus	*cerris*	3	3	3	3	12
Quercus	*palustris*	3	3	3	3	12
Fraxinus	*excelsior*	3	3	2	3	11
Fraxinus	*angustifolia*	3	3	2	3	11
Fraxinus	*uhdei*	3	3	2	3	11
Fraxinus	*velutina*	3	3	2	3	11
Aesculus	*hippocastanum*	3	3	2	3	11
Carpinus	*betulus*	3	3	2	3	11
Ostrya	*carpinifolia*	3	3	2	3	11
Juglans	*regia*	3	3	2	3	11
Zelkova	*serrata*	3	3	2	3	11
Ulmus	*americana*	3	3	3	2	11
Platanus	*x acerifolia*	3	3	3	2	11
Liriodendron	*tulipifera*	3	3	3	2	11
Cedrus	*atlantica*	3	3	3	2	11
Cedrus	*deodara*	3	3	3	2	11
Cedrus	*libani*	3	3	3	2	11
Taxus	*baccata*	3	2	3	3	11
Species excluded considering the specific ecological indices (Temperature and Continentality)						
Fagus	*sylvatica*	3	3	3	3	12
Pseudotsuga	*menziesii*	3	3	3	3	12
Abies	*alba*	3	3	3	2	11
Picea	*abies*	3	3	3	2	11
Alnus	*glutinosa*	3	3	2	3	11
Pinus	*radiata*	3	2	3	3	11

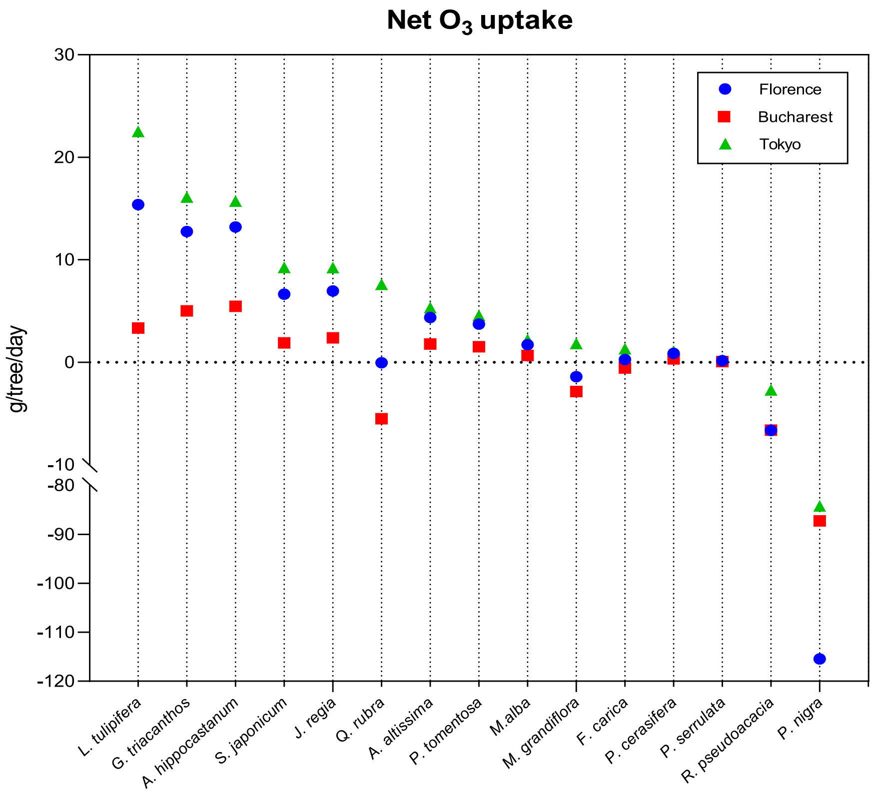

Fig. 1. City-specific values of net O_3 uptake (in g $tree^{-1}day^{-1}$). Values under the zero line indicates O_3 formation.

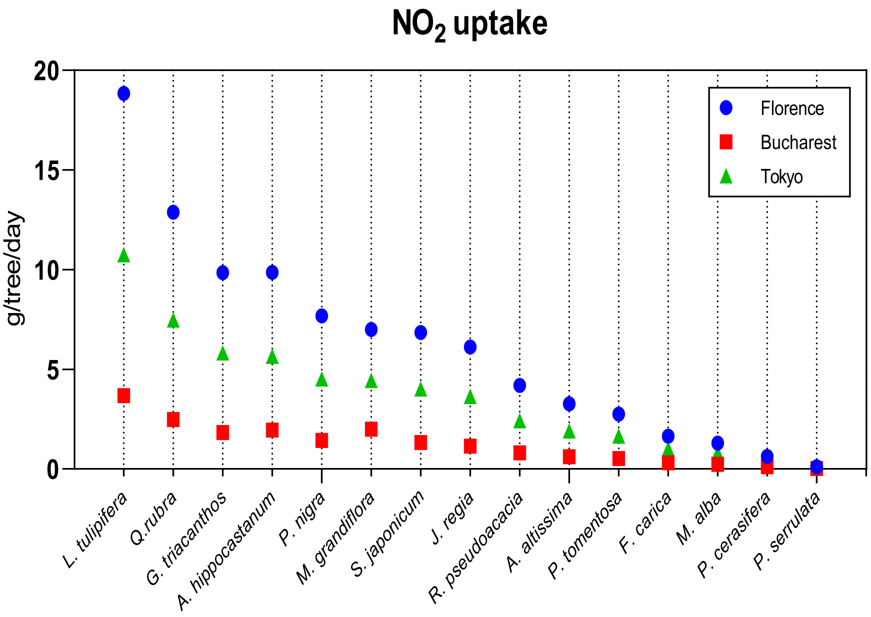

Fig. 2. City-specific values of NO_2 removal (in g $tree^{-1}day^{-1}$).

3.5. *Comparison between species in different cities*

The 15 species common to Florence, Bucharest and Tokyo showed dissimilar pollutant removal capabilities (Supplementary Table S5). Overall, net O_3 uptake was higher in Tokyo, followed by Florence and then Bucharest (Fig. 1). *Liriodendron tulipifera* was the best performer regarding net O_3 uptake both in Florence and Tokyo (15.39 and 22.52 g $tree^{-1}day^{-1}$ respectively) while in Bucharest *A. hippocastanum* showed the highest value (5.47 g $tree^{-1}day^{-1}$). Conversely, *Populus nigra* reached the lowest value in each city. Moreover, *Quercus rubra* and *Magnolia grandiflora* showed negative net O_3 uptake in the European cities but the O_3 balance was positive in Tokyo.

NO_2 removal was higher in Florence followed by Tokyo and Bucharest (Fig. 2). Also in this case, *L. tulipifera* was the best performing species while trees belonging to *Prunus* genus showed the lowest results. On the contrary, PM_{10} deposition was higher in Tokyo than in Florence and Bucharest (Fig. 3). Only the evergreen *M. grandiflora* removed more PM_{10} from the air in the European cities than in Tokyo although the differences were minimal.

4. Discussion

We developed an extensive and comparative database (Annex 1) about the removal properties of atmospheric pollutants by 221 species commonly found in urban green areas. Specific models for net O_3 uptake, NO_2 absorption, PM_{10} abatement and CO_2 storage and sequestration were developed and applied to different species, encompassing tall trees, small trees, and shrubs.

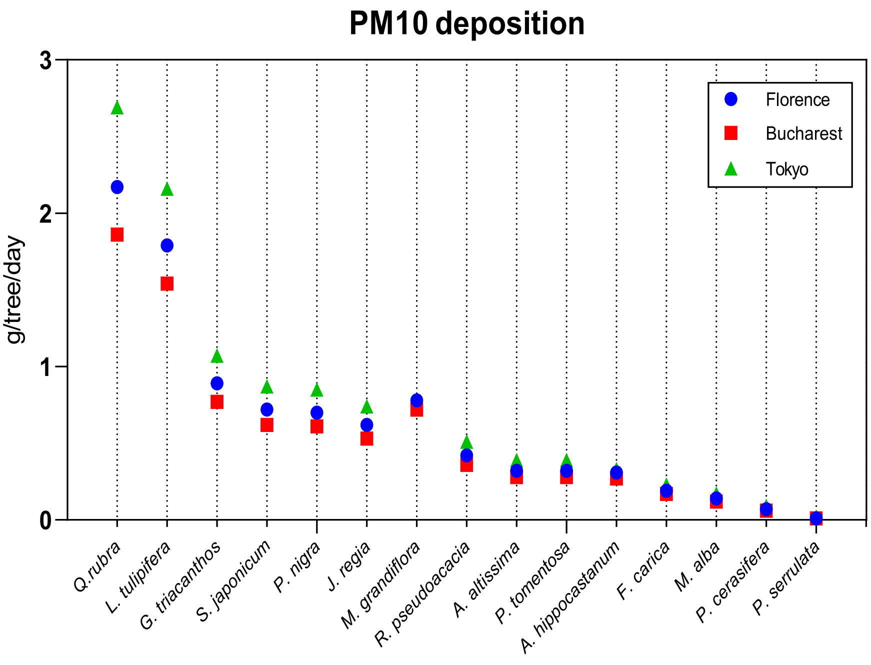

Fig. 3. City-specific values of PM_{10} deposition (in g $tree^{-1}day^{-1}$).

4.1. Species-specific pollution removal modelling

For gaseous pollutants (O_3 and NO_2), the novelty of the FlorTree model was to consider the species-specific g_{max}. In fact, previous studies did not consider species-specific stomatal conductance parameters (Hirabayashi et al., 2011; Bottalico et al., 2017; Tiwari and Kumar, 2020). For example, Bottalico et al. (2017) applied only a generic g_{max} per forest category such as broadleaved deciduous or broadleaved evergreen types. However, g_{max} largely varies with species (0.024–0.657 mol m^{-2} s^{-1} in this study) depending on leaf habit (deciduous/evergreen), morphology (conifer/broadleaf), longevity and water use strategy (Hoshika et al., 2018).

For PM_{10} deposition, i-Tree Eco dry deposition model (Hirabayashi et al., 2011) and other models (Manes et al., 2016; Bottalico et al., 2017), used a constant deposition velocity while Pace and Grote (2020) differentiated it by categories (broadleaf or conifer). On the contrary, FlorTree developed a simple empirical model that includes species-specific parameters for the target leaf/shoot morphology (shoot silhouette to total leaf area ratio - STAR, leaf size - LS, presence of leaf hairiness - TR, phyllotaxis - PT and specific leaf area - SLA). According to our statistical analysis, the most meaningful parameters were STAR and PT indicating that complex shoot/leaf structure and disposition are more relevant for PM_{10} deposition than the presence of trichomes and hairs or leaf size/area. These results are in agreement with Sgrigna et al. (2020) showing that trichomes density was not a decisive feature for PM deposition in 12 tree species. Also Xie et al. (2022) stated that crown morphological structures have a greater impact on particulate retention than leaf traits.

For CO_2 storage and sequestration, we exploited a new empirical approach that considers species-specific woody density and stem volume across a range of plant ages. Differently to our approach, previous studies (e.g., Nowak and Crane, 2002) settled the average annual diameter growth at 0.61 cm for park trees without making a species-specific distinction. Therefore, FlorTree allows more reliable estimates of CO_2 uptake taking into consideration both species and annual growth deriving from a recently developed dataset for urban trees (McPherson et al., 2016). The annual species-specific CO_2 sequestration that we found (range 8–111 kg CO_2 tree^{-1} year^{-1}) is similar to Baraldi et al. (2019) where a range of 13–74 kg CO_2 tree^{-1} year^{-1} was detected for urban trees and shrubs calculated by iTree Eco model for medium size tree.

4.2. Species selection for urban greening in Florence

The final database is the result of a collection of several species-specific traits and can be an important tool for urban planners and administrations, as it offers guidelines for future plantations.

We exploited the database to choose the most suitable species to plant in Florence urban context showing the best performance for the removal/abatement of O_3, NO_2, PM_{10} and CO_2. To be noted that the final selection should consider other co-factors such as: pollen allergenicity (Cariñanos et al., 2019), invasiveness (Dickie et al., 2014), drought tolerance and pest and disease resistance (Sicard et al., 2018). The final list included 24 high trees (4 conifers and 20 broadleaves) although careful attention to co-factors should be required for some of these species despite their excellent ability to remove air pollutants.

According to our analysis, *Tilia cordata, Tilia platyphyllos* and *Tilia x europaea* showed the best features (high canopy dimensions at maturity, relatively high g_{max} and no bVOC emissions) to counteract atmospheric pollution and were highly suitable to be planted in Florence. Furthermore, as reported by Tenche-Constantinescu et al. (2015), linden species are considered accumulators of heavy metals (mostly Pb) and are recommended to be used in urban landscapes for their resistance to abiotic and biotic stress. However, due to global warming, Weryszko-Chmielewska et al. (2019) discovered accelerated flowering and pollen release in *Tilia* species in central Europe suggesting that new linden tree plantations should be at some distance from residential areas, although Cariñanos and Marinangeli (2021) considered that these species are moderately allergenic.

Also, *Acer negundo*, *Acer platanoides* and *Acer pseudoplatanus* achieved strong performance in pollutants removal. Maples have generally a low OFP thus enhancing their net O_3 removal capacity while their wide crown has a relatively high potential to capture PM_{10}. In addition, in autumn, their leaves turn red/yellow colors providing another important ecosystem service for urban landscape, i.e. aesthetic (Wei, 2019). Although *A. negundo* cannot be fully recommended for urban greening due to its invasiveness (Morozova, 2021), planting only male trees could be envisaged as it is a dioecious species. On the contrary, *A. pseudoplatanus* and *A. platanoides* could not be considered due to their low tolerance to the summer dry climate and high temperature of Florence. These species would be more suitable for planting in cooler climate regions such as Northern Europe. Other species belonging to *Acer* genus are worth investigating for urban environment such as *Acer campestre* (10 points) indicated by Swoczyna et al. (2010) among the most tolerant taxa of roadside conditions.

Quercus species at maturity have generally adequate features to be excellent pollutant removers, such as big crowns and good stomatal conductance. Despite this, most of *Quercus* species exhibits strong emission of bVOCs leading to negative net O_3 balance (Karlik and Pittenger, 2012). For instance, *Quercus robur* and *Quercus pubescens* are acknowledged as high isoprene emitters (Fitzky et al., 2019), while *Quercus ilex* is characterised by strong monoterpene emissions (Karl et al., 2009).

An exception is *Quercus cerris* that is a moderate bVOC emitter (Calfapietra et al., 2009) and can be considered a good candidate since it shows anisohydric behavior and keeps stomata open also during hot summer days when tropospheric concentrations of O_3 are usually higher (Grote et al., 2016; Cotrozzi et al., 2017). Also *Q. palustris* could be selected (12 points) and it seems to display the positive feature of tolerating low levels of oxygen in the soil (Watson and Kelsey, 2006).

Ash trees (*Fraxinus excelsior*, *Fraxinus angustifolia*, *Fraxinus uhdei* and *Fraxinus velutina*) could be other interesting candidates. However, *F. excelsior* is a hygrophilous species and *F. velutina* is even more sensitive to drought than *F. excelsior* (Percival et al., 2006). Therefore, these species should be placed in shaded sites and watered for several years after planting.

Conifers are generally known to make a beautiful tree shape and maintain greenness throughout the year in an urban context (Relf et Appleton, 2000). The best conifer performers were *Cedrus libani, Cedrus atlantica* and *Cedrus deodara*. These species showed prominent capabilities to capture PM_{10} from the air and could be planted in areas characterised by high levels of fine dust. However, these species spend many years to achieve their size at maturity delaying their effectiveness in PM_{10} abatement. *Taxus baccata* should be avoided because of its ecosystem disservices since the entire plant is poisonous, with the exception of the aril (Von Döhren and Haase, 2022).

Among deciduous trees, we found other good candidates, but caution is required to use them for urban greening. For instance, *Carpinus betulus* and *Ostrya carpinifolia*, while demonstrating excellent abilities mainly in gaseous pollutant removal, should not be planted in groups due to their high allergenicity (Cariñanos and Marinangeli, 2021). *Ulmus* species, *Aesculus hippocastanum* and *Platanus x acerifolia,* despite their adaptability to Florence climate, could suffer biotic and abiotic stress (Lazarević and Davydenko, 2022). For *Ulmus* species, it is recommended to use patented clones resistant to *Ophiostoma ulmi*, etiological agent of "Duch Elm Disease" (DED), e.g., "Fiorente", "Arno" and "San Zanobi" that show rapid growth and upright habit while "Plinio" can be used as an ornamental shade tree thanks to its vase-shaped canopy (Santini et al., 2007; Santini et al., 2012).

Aesculus hippocastanum suffers attacks from *Cameraria orhidella* which involves significant leaf damage during summer with repercussions on photosynthesis (Percival et al., 2011) and aesthetic value (early apoptosis). Moreover, *A. hippocastanum* poorly tolerates pruning operations and, therefore, it may be recommended in parks rather than in tree-lined avenues. *Platanus x acerifolia* could be used as street tree in cities but extreme attention must be paid to the widespread and devasting fungal disease *Ceratocystis platani* (Walter) Engelbrecht & Harrington as well as summer heatwaves (Sanusi and Livesley, 2020) inducing significantly canopy loss and consequently lower air pollutant removal efficiency.

Interestingly enough, an important species commonly present in urban environment such as *Quercus ilex* (9 points) was excluded from this list. The reason is that it is a strong bVOC emitter and its OFP overcomes O_3 removal. However, in urban contexts characterised by high concentrations of PM_{10} and low levels of O_3, planting an evergreen species such as *Quercus ilex* could be a good choice despite its bVOC emissions and negative net O_3 uptake.

4.3. *Comparative analysis of pollutant removal in different local conditions*

Interesting results raised up from the comparison of the 15 species commonly used in urban greening of the three cities investigated. Different climate and pollution conditions (Supplementary table S6) led to a partial change in the air pollutants removal by trees. In particular, *Quercus rubra* had a positive O_3 removal from the air in Tokyo while this species was an O_3 emitter in the two European cities. Tokyo has a humid climate during summer (RH greater than 80%) while climatic conditions in the two European cities are relatively dry. A high relative humidity (and low VPD) in Tokyo allowed *Q. rubra* to keep stomata open during summer resulting in a stronger performance in the uptake of O_3. Furthermore, bVOC emissions, and consequently OFP, are strongly dependent on light intensity and air temperature (Owen et al., 2002). Therefore, OFP led to lower values in Tokyo than in Florence, where the Mediterranean climate is typically characterised by intense solar radiation and temperature peaks $> 40\ ^\circ C$ during the summer. However, future climate change and temperature increase could potentially lead to an increase of OFP, suggesting that *Q. rubra* and oak trees should not be planted in Tokyo in the next years.

Regarding PM_{10} deposition, a slightly higher removal was detected in Tokyo despite lower annual PM_{10} averages were detected in this city than in the other ones. This can be mainly explained with an average higher wind speed, maybe due to its coastal location, allowing a greater deposition of PM_{10} on tree canopies. Indeed, a positive correlation between wind speed and PM_{10} leaf-deposition was highlighted by other authors for evergreen shrubs (Mori et al., 2015).

Finally, species-specific NO_2 uptake showed the same behavior for each city with the following rank order: Florence > Tokyo > Bucharest. The same rank was observed for NO_2 concentration in the three cities in both winter and summer. Therefore, higher stomatal uptake in Florence could be simply linked to higher concentration of NO_2.

5. Conclusions

We proved that the newly-developed single-tree FlorTree model is useful for species selection in urban green areas and can be applied to different climate and pollution conditions. FlorTree has the great advantage to be highly species-specific (maximum stomatal conductance, bVOC emission and leaf-trait based deposition velocity) and easy to apply in a given urban context where meteorological data and pollutant concentrations are available. Indeed, FlorTree may be adopted as decisional tool by urban planners, landscape architects and authorities to choose the correct species for ensuring better air quality in a given city via the green infrastructure. In particular, for Florence our results suggest that 24 species offered optimal performances for air pollutant removal. Among them hardwoods, with large crowns at maturity such as linden, maple, and ash, are generally better for the removal of gaseous pollutants, while conifers are to be preferred if we have high levels of PM_{10} in the air. Conversely, *Quercus*, *Populus* and *Eucalyptus* species should be avoided in areas with high concentrations of O_3 considering their high bVOC emissions. However, we demonstrated that different local conditions of weather and air pollution may change the species-specific responses. For instance, some species, such as *Quercus rubra*, may show a positive or negative O_3 uptake depending on the local climate. Therefore, planting “the right species at the right place” is crucial to maximise an important ecosystem service offered by urban trees such as air pollution removal.

Nevertheless, further research and constant updates are needed to improve the knowledge about species-specific input parameters that inevitably can vary according to measuring and climatic situations.

CRediT authorship contribution statement

Yasutomo Hoshika, Jacopo Manzini, Elisa Carrari, Elena Paoletti: Conceptualization. **Yasutomo Hoshika, Jacopo Manzini, Elisa Carrari**: Methodology, Data curation. **Jacopo Manzini, Yasutomo Hoshika**: Writing – original draft preparation. **Jacopo Manzini, Yasutomo Hoshika, Elisa Carrari, Pierre Sicard, Makoto Watanabe, Ryoji Tanaka, Ovidiu Badea, Francesco Paolo Nicese, Francesco Ferrini, Elena Paoletti**: Writing – review & editing. **Elena Paoletti**: Supervisions. All authors have read and agreed to the published version of the manuscript.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2023.127967.

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