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Shrubs Matter: An Evaluation of the Capacity of Nine Shrub Species to Dissipate Latent Heat and to Remove CO_2 and Airborne PM

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Abstract

The aim of this research was to quantify the capacity of different shrub species to remove atmospheric CO_2, to adsorb particulate matter and to dissipate latent heat through transpiration. A total of 308 established plants comprising *Deutzia scabra*, *Elaeagnus* × *ebbingei*, *Euonymus japonicus*, *Forsythia* × *intermedia*, *Laurus nobilis*, *Ligustrum vulgare*, *Pittosporum tobira*, *Prunus laurocerasus* and *Viburnum tinus* were selected in Lugano (Switzerland) and Bolzano (Italy). Stem diameter, crown radius, Leaf Area Index, net CO_2 assimilation per unit leaf area (A_{leaf}), transpiration, and stomatal conductance (g_s) were measured during spring, summer, and fall. The net CO_2 assimilation per unit of crown projection area and per plant were calculated by upscaling A_{leaf} using a multilayer model. Latent heat dissipation was calculated using the Penman–Monteith equation. The amount of PM trapped on leaves was measured using a gravimetric method. Differences in leaf area and leaf gas exchange among species affected their capacity to deliver specific ecosystem services. *Forsythia*, *Pittosporum*, *Elaeagnus* and *Deutzia* removed about 40% more CO_2 per unit crown projection area than *Laurus*, *Ligustrum*, and *Euonymus*. Latent heat dissipation by shrubs was, on average, 130 W m^{-2}, which is comparable to that of tree species. PM removal per unit leaf area was higher in species with sparse canopies and rough leaf surfaces.

Keywords: allometric equations; CO_2 assimilation; latent heat; Leaf Area Index; particulate matter; ecosystem services

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1. Introduction

Urban vegetation can contribute to the well-being of city dwellers through the delivery of provisioning, environmental regulation and support, and cultural ecosystem services [1]. A growing body of research focuses on methods and parameters to quantify the delivery

of ecosystem services (ES) by urban vegetation species [2–5]; however, most studies deal with tree species. While data about shrubs are rarer [6], the value of shrubs should not be underestimated. Unlike trees, they can be planted in very small spaces, along road edges where they do not pose any risk of interference with vehicular traffic, nor risk causing negative impact on air quality, which happens for large trees in urban street canyons [7]. Shrubs are known to effectively contribute to the removal of atmospheric particulate matter. According to the *Lancet* report for 2025, deaths attributable to total ambient $PM_{2.5}$ air pollution increased from 7.5 million deaths in 2010 to 8.5 million deaths in 2022 (7.6% increase); while deaths attributable to ambient $PM_{2.5}$ air pollution from human activities grew from 5.9 million in 2010 to 6.5 million in 2022 (11.3% increase) [8].

The effectiveness of shrubs to reduce atmospheric CO_2, estimated as carbon storage (C-storage) (i.e., the amount of atmospheric carbon trapped as organic carbon in the woody biomass of the tree) or C-sequestration (i.e., the change in carbon storage over 1 year) [9], is generally reported as low, because of their smaller size and biomass at maturity compared to trees [10]. Nonetheless, the contribution of vegetation to CO_2 removal may be better represented by net photosynthetic carbon gain (i.e., the amount of atmospheric CO_2 annually removed by vegetation through photosynthesis, net of respiratory losses) [4]. Shrubs can develop high Leaf Area Index (LAI) and can have high photosynthetic rate per unit leaf area, thus their role in CO_2 removal may be higher than previously thought [6]. Direct measurements of CO_2 assimilation have seldom been conducted in situ at urban sites, and in most cases, they were performed only on full-sun leaves [11]. Conversely, the parametrization of shaded leaves is crucial to upscale photosynthesis from leaf-scale to canopy-scale using sun–shade models, which were shown to be more accurate than big-leaf models [12].

Similarly, most of the research that evaluated the capacity of urban vegetation to ameliorate microclimate mostly focused on trees [13–15]. Due to larger canopy size and total leaf area, trees are expected to shade (i.e., reduce the amount of short-wave radiation reaching surfaces and buildings, and consequently, heat accumulation) and to dissipate latent heat through transpiration more efficiently than shrubs [16]. Nonetheless, the shrub layer can positively contribute to urban canopy cover, which is a major determinant of cooling benefits [17], and the use of shrub species that sustain a high stomatal conductance during hot periods may help the city to become more climate-proof.

Finally, the effect of shrubs on air particulate matter (PM) reduction, especially when forming 'vegetation barriers' or 'green belts' along roads, was studied in situ in a limited number of species [18–20]. Vegetation can passively ameliorate air quality through two main mechanisms: deposition and dispersion. Pollutant particles can be deposited on plant surfaces (i.e., bark and leaves) by rain and snow or by gravity, inertia and Brownian motion (deposition mechanism). At the same time, plants can alter air currents and turbulence simply through their physical presence, influencing the local concentration of pollutants (dispersion mechanism) [21]. The value of shrubs compared to trees in this field is particularly relevant. Shrub-specific traits, such as the canopy structure (often multi-stemmed and branched from the ground) and the limited height, allow for the creation of thick and dense green barriers very close to vehicular emission sources of air PM, efficiently reducing pedestrian exposure to air pollution in open road conditions [7]. Even in urban street canyons, shrubs are more effective than large trees. The latter of the two, even when able to trap many particles, still does not prevent the flow of air pollutants at the pedestrian level because their crowns are generally above the average human breathing height of 1.5 m [7]. For all these reasons, more attention should be paid to the evaluation of the capacity of shrub species to ameliorate air quality. Despite the relevance of these processes, relatively few studies have specifically quantified the ecosystem services provided by

shrubs in urban environments, and the available literature on shrub-derived benefits remains limited.

This research used two cities (Lugano, Switzerland; Bolzano, Italy) as living laboratories to test in situ the hypothesis that the capacity to assimilate CO_2, dissipate latent heat through transpiration, and remove atmospheric PM differs among shrub species due to differences in physiological traits and leaf area. Additionally, we tested the idea that ES provisioning may vary across different seasons depending on the meteorological variables of the planting site. These findings will provide useful support for decision makers during the selection of shrub species for urban planting in order to maximize plant and human wellbeing.

2. Materials and Methods

2.1. Experimental Sites and Plant Material

The research was carried out in Lugano (Switzerland) and Bolzano (Italy). Both cities have a temperate, mild and humid climate (Cfb, according to the Koppen–Geiger classification). The average air temperature over the last 30 years is 14.0 °C in Lugano and 13.1 °C in Bolzano. January is the coldest month in both cities (average temperatures are 3.8 °C and 1.8 °C in Lugano and Bolzano, respectively), and July is the warmest month, with an average temperature of 22.6 °C in Lugano and 23.7 °C in Bolzano. Rainfall is evenly distributed throughout the year in both cities, and the average annual rainfall is substantially higher in Lugano (1658 mm per year) than in Bolzano (1111 mm per year). Over the experimental period (January 2020 to December 2020 for Lugano and January 2021 to December 2021 for Bolzano), daily weather data were obtained from the local weather stations of the two cities (MeteoSwiss for Lugano, Open data Alto Adige for Bolzano), while daily air pollutant data were obtained from local stations (OASI—Osservatorio Ambientale della Svizzera Italiana for Lugano, Agenzia provinciale per l'ambiente e la tutela del clima for Bolzano) (Table 1).

Table 1. Meteorological and air quality data from the experimental sites of Lugano (a) and Bolzano (b) across a 16–17-day period (pre-sampling period of 14 days plus 2–3 sampling days).

City	Sampling Period	Season	Precipitation, Cumulative Values (mm)	Wind Velocity (m s^{-1})	$PM_{2.5}$ Concentration (μg m^{-3})	PM_{10} Concentration (μg m^{-3})
(a) Lugano	16 to 18 June 2020	spring	294.0	1.47	4.21	8.25
	27–28 July 2020	summer	25.5	1.54	7.69	13.68
	16–17 September 2020	fall	16.8	1.23	11.47	18.67
	12 to 14 January 2021	winter	50.3	1.28	14.55	19.94
(b) Bolzano	26–27 May 2021	spring	38.2	1.58	4.26	7.62
	20–21 July 2021	summer	64.6	1.56	7.52	12.51
	30 September to 1 October 2021	fall	47.3	1.07	8.83	13.91
	26–27 January 2021	winter	32.7	1.19	15.51	23.94

During the experimental years (2020 and 2021), the annual average air PM_{10} and $PM_{2.5}$ concentrations obtained from the local stations were 18.5 and 12.3 μg m^{-3}, respectively, in Lugano, and 17.2 and 11 μg m^{-3} in Bolzano. In both cases, the values were above the WHO guideline recommendations (annual averages of PM_{10} < 15 μg m^{-3} and $PM_{2.5}$ < 5 μg m^{-3}; [22]), and $PM_{2.5}$ also exceeded the new thresholds recently proposed for Europe (annual averages of PM_{10} < 20 μg m^{-3} and $PM_{2.5}$ < 10 μg m^{-3}) [22]. Weather and average daily air PM_{10} and $PM_{2.5}$ concentrations are reported for the different measurement days in Tables 1 and 2. During the sampling days, air PM_{10} concentration never exceeded the WHO recommendations (PM_{10} < 45 μg m^{-3}; 24-h average) while air $PM_{2.5}$

concentrations slightly exceeded the WHO recommendations ($PM_{2.5}$ < 15 μg m^{-3}; 24-h average) in Bolzano during winter.

Table 2. Average temperature and cumulative precipitation in the experimental site of Lugano (a) and Bolzano (b) compared to the average values of the last thirty years: spring (01/05 to 21/06), summer (22/06 to 31/08), fall (01/09 to 15/10) and winter (01/01 to 29/02).

City	Year	Season	Precipitation, Cumulative Values (mm)	Precipitation, Avg Last Thirty Years (mm)	Temperature (°C)	Temperature, Avg Last Thirty Years (°C)
(a) Lugano	2020	spring	510	164	19.7	19.6
		summer	50	153	23.1	22.1
		fall	130	185	18.9	17.5
		winter	175	127	5.2	4.4
(b) Bolzano	2021	spring	98	70	17.3	18.0
		summer	133	87	24.4	24.7
		fall	47	70	21.1	18.5
		winter	180	52	2.3	1.5

Six shrub species per city were selected based on their relevance in the existing plant inventories and their even distribution in the cities. The list of species, their abbreviations, the number of plants on which growth traits were assessed, and their minimum and maximum stem diameters and crown projection area are reported in Table 3. Three of the six species [the deciduous *Forsythia* × *intermedia (Fi)*, the evergreen *Pittosporum tobira (Pt)* and *Prunus laurocerasus (Pl)*] were measured in both cities. The evergreen *Elaeagnus* × *ebbingei (Ee)* and *Laurus nobilis (Ln)* and the semi-deciduous *Ligustrum vulgare (Lv)* were only measured in Lugano. The deciduous *Deutzia scabra (Ds)* and the evergreen *Euonymus japonicus (Ej)* and *Viburnum tinus (Vt)* were only sampled in Bolzano. To representatively sample the shrub population, the location of the selected shrub species growing in each city was retrieved using the existing city inventory implemented into GREENSPACES software (R3GIS, Bolzano, Italy). Nine (Lugano) and eight (Bolzano) blocks containing at least 2 individuals of every selected species were established in each city. The blocks were evenly distributed and included public parks, school gardens, and roadside vegetation (Figure A1 in Appendix A). Shrubs growing solitary or in shrubby patches were preferred over those growing in formal hedges.

Table 3. Species selected in the experimental cities of Lugano (a) and Bolzano (b), their abbreviations, and the number of plants on which biometrics parameters were measured. D_{30min} (cm), D_{30max} (cm) and CPA_{min} (m^2), CPA_{max} (m^2) indicate the observed minimum and maximum stem diameters and crown projection areas, respectively. H_{avg} (m) indicates the average plant height recorded. Standard deviation is reported for H_{avg}. E, D, SD in brackets in the species column indicate their leaf persistence: evergreen, deciduous and semi-deciduous, respectively. n is the number of analyzed shrubs per species.

City	Species	Abbreviation	n.	D_{30min} (cm)	D_{30max} (cm)	CPA_{min} (m^2)	CPA_{max} (m^2)	H_{avg} (m)
(a) Lugano	*Elaeagnus* × *ebbingei* (E)	Ee	23	4.47	18.60	0.86	20.39	2.01 ± 0.7
	Forsythia × *intermedia* (D)	Fi	24	3.85	15.34	1.43	19.15	3.13 ± 1
	Laurus nobilis (E)	Ln	22	4.02	42.70	0.23	16.38	2.97 ± 2.4
	Ligustrum vulgare (SD)	Lv	23	3.17	12.00	0.35	8.79	1.91 ± 0.4
	Pittosporum tobira (E)	Pt	24	3.39	36.47	1.09	35.45	2.20 ± 1.5
	Prunus laurocerasus (E)	Pl	24	7.49	27.80	0.43	9.84	2.44 ± 0.7
(b) Bolzano	*Deutzia scabra* (D)	Ds	30	2.48	17.70	0.28	15.16	2.20 ± 0.9
	Euonymus japonicus (E)	Ej	18	2.74	22.98	0.50	32.12	2.10 ± 1.2
	Forsythia × *intermedia* (D)	Fi	30	2.14	11.78	0.49	10.70	2.23 ± 0.9
	Pittosporum tobira (E)	Pt	30	6.70	25.43	0.78	35.44	2.44 ± 0.9
	Prunus laurocerasus (E)	Pl	30	2.37	31.86	0.64	77.70	2.22 ± 1.2
	Viburnum tinus (E)	Vt	30	2.33	14.48	0.33	6.67	2.02 ± 0.6

2.2. Growth and Leaf Area Index

Biometric measurements were performed in January 2021 on all individuals of the selected species growing in the experimental areas (140 and 158 plants in Lugano and Bolzano, respectively). The number of stems and their diameter, crown radius and plant height were recorded. Stem diameters (D_{30}) were measured at 30 cm from the ground [23] with a caliper, by making two measurements perpendicular to each other and averaging the measured values. For shrubs with less than six stems, all the diameters were measured, then the radius (r = d/2) and the corresponding basal stem area ($A = \pi\ r^2$) were calculated. The areas of the individual stems were summed (A_{tot}), then the overall stem radius (r_{tot}) and diameter (D_{tot}) were calculated as: $r_{tot} = \sqrt{A_{tot}/\pi}$; $D_{tot} = 2 \times r_{tot}$). For shrubs with more than six stems, six representative stems were chosen and their diameters measured. The average basal area of the 6 stems was calculated, then multiplied by the number of stems to get A_{tot}. r_{tot} and D_{tot} were calculated as described previously. Crown projection area (*CPA*) was calculated from two orthogonal crown diameter measurements, performed using a mm accuracy diameter tape in the North–South and East–West direction as: $CPA = \pi \times (d_{NS}/2 \times d_{EW}/2)$. Plant height was measured using a cm accuracy diameter tape.

The effective Plant Area Index (PAI_e, $m^2\ m^{-2}$) was measured using an Accupar ceptometer (Accupar LP-80, Decagon Devices, Washington, DC, USA) during bright days (PAR > 1300 µmol $m^{-2}\ s^{-1}$ and progressive change in PAR < 75 µmol $m^{-2}\ min^{-1}$) in July 2020 and July 2021. Measurements were carried out between 11:30 and 14:30 (CET) [24], on the same shrubs subjected to the eco-physiological measurements. Four readings of above-canopy irradiance (measured by positioning the ceptometer horizontally above the canopy) and below-canopy irradiance were collected per plant [25]. To account for Woody Area Index (*WAI*, $m^2\ m^{-2}$), a *WAI*/*PAI* ratio (α) of 0.25 was assumed based on available literature on shrubs [26–28]. To account for the non-normal leaf distribution within the canopy, clumping (Ω) was calculated as described by [29], assuming a uniform vertical profile of PAI_e. Leaf Area Index (*LAI*, $m^2\ m^{-2}$), i.e., half of total leaf surface area per unit ground surface area, was calculated as:

$$LAI = (1 - \alpha) \times PAI_e/\Omega \quad (1)$$

2.3. Eco-Physiological Measurements

2.3.1. Net CO_2 Assimilation

Net CO_2 assimilation per unit leaf area (A_{leaf}, µmol $m^{-2}\ s^{-1}$) was measured using an infra-red gas analyzer (Ciras-2, PP-System, Amesbury, MA, USA). Measurements were conducted during spring (Lugano: 16–18 June 2020; Bolzano: 26–27 May 2021), summer (Lugano: 27–28 July 2020; Bolzano: 20–21 July 2021) and fall (Lugano: 16–17 September 2020; Bolzano: 30 September–1 October 2021) between 9:00 and 17:00 (CET). Four fully expanded leaves per plant were measured (for a total of 648 and 576 leaves over the entire experiment in Lugano and Bolzano, respectively). Leaves were chosen after ideally dividing the canopy into two layers along its vertical profile: an apical (a) and a basal (b) layer, each representing 50% of the live canopy height. Within each layer, one external leaf fully exposed to solar irradiance (denoted as "ae" and "be" for apical and basal layers, respectively) and one internal leaf to the canopy subjected to self-shading (denoted as "ai" and "bi" for apical and basal layers, respectively) were analyzed. The IRGA was set to supply the leaves with a 400 ppm external CO_2 concentration, 70% of external RH, while the irradiance provided was different depending on the leaf position. External leaves (ae;

be) were exposed to saturating irradiance (1300 µmol m^{-2} s^{-1}), while internal leaves (ai; bi) were exposed to species-specific irradiance values, which were set as follows:

$$PAR_{shade} = PAR_{sun} \times \tau \quad (2)$$

where PAR_{sun} is the above-canopy PAR, while τ is the transmittance in the apical (τ_{ai}) and basal (τ_{bi}) layers of the canopy (Table A1 in Appendix A). τ_{ai} and τ_{bi} were obtained as the ratio between the PAR measured inside the canopy (in the apical and basal layer, respectively) and above the canopy [4]. PAR_{shade} was in the range of 88–862 µmol m^{-2} s^{-1} (ai leaves) and 50–495 µmol m^{-2} s^{-1} (bi leaves), depending on species and solar zenith angle (θ).

According to the multilayer approach, the crown was divided into two layers, each made of sun and shaded leaves [29]. The *LAI* of each layer was partitioned between sun and shade using the equations:

$$LAI_{sun} = 2\cos\theta \times (1 - e^{-0.5 \times \Omega \times LAI/\cos\theta}) \quad (3)$$

$$\text{and } LAI_{shade} = LAI - LAI_{sun} \quad (4)$$

The net CO_2 assimilation per unit crown projection area (A_{cpa}, g m^{-2} ground h^{-1}) was calculated as (More information in Appendix A):

$$A_{cpa} = 0.5 \times (A_{ae} \times LAI_{sun} + A_{ai} \times LAI_{shade}) + 0.5 \times (A_{be} \times LAI_{sun} + A_{bi} \times LAI_{shade}) \quad (5)$$

The total net CO_2 assimilation per plant (A_{plant}, g $plant^{-1}$ h^{-1}) was then calculated by multiplying A_{cpa} and *CPA*.

2.3.2. Stomatal Conductance and Latent Heat Dissipation

Daily latent heat dissipation by transpiration was calculated using a one-step Penman–Monteith approach. Transpiration per unit leaf area (E_{leaf}, mmol m^{-2} s^{-1}) and stomatal conductance to water vapor (g_s, mmol m^{-2} s^{-1}) were measured as previously described for A_{leaf} in Section 2.3.1. Nighttime measurements of g_s were also conducted between 23.00 and 01.00 (CET). The environmental variables needed to run the equation were obtained from the local weather stations of the two cities (MeteoSwiss for Lugano, Open data Alto Adige for Bolzano). The latent heat flux due to transpiration per soil square meter (LH_{cpa}; W m^{-2}) was calculated on a daily scale, according to [30] (modified from [31]):

$$LHcpa = \frac{\Delta Q + \rho_a C_p \frac{VPD}{R_a}}{\Delta + \gamma\left(1 + \frac{R_s}{R_a}\right)} \quad (6)$$

where Q is the available energy in W m^{-2}; ρ_a is the mean air density at constant pressure (1.22 kg m^{-3}); C_p is the specific heat of air (1.013 kJ $kg^{-1}K^{-1}$); Δ represents the slope of the saturation vapor pressure–temperature relationship; R_a is the aerodynamic resistance; and R_s is the surface resistance.

The contribution of each type of leaf (sun/shade) in each layer (apical/basal) to latent heat dissipation was calculated from independent measurements of g_s values conducted on ae, ai, be and bi leaves, both during the day and at night ($LH_{cpa,day}$ and $LH_{cpa,night}$). LH_{cpa} was then calculated as (more information in Appendix A):

$$LH_{cpa} = LH_{cpa,day} + LH_{cpa,night} \quad (7)$$

2.3.3. Air Particulate Matter Removal

Air particulate matter removal was assessed by in situ leaf sampling and subsequent ex situ laboratory analysis. Sampling was performed in spring (Lugano: 16–18 June 2020; Bolzano: 26–27 May 2021), summer (Lugano: 27–28 July 2020; Bolzano: 20–21 July 2021), fall (Lugano: 16–17 September 2020; Bolzano: 30 September–1 October 2021) and winter (Lugano: 12–14 January 2021; Bolzano: 26–27 January 2021) on the same shrubs selected for biometrics and eco-physiological traits. A leaf sample representative of the entire crown was collected from each shrub, resulting in 54 samples in Lugano and 48 in Bolzano for each of the spring, summer, and fall seasons. During winter, only evergreen and semi-deciduous species were sampled, for a total of 45 and 32 samples in Lugano and Bolzano, respectively. Thus, a total of 207 samples in Lugano and 176 samples in Bolzano were analyzed over the entire experiment. Samples were manually collected, immediately stored at −20 °C and analyzed within one week. Each sample, made of about 300–400 cm^2 leaf area, was analyzed with a gravimetric technique described in detail in [32]. The number of leaves needed to cover the required sampled area depended on leaf size. To quantify PM_x accumulation per unit leaf area (μg cm^{-2}) (i.e., the amount of PM_x on the leaf surface at the time of sampling), each leaf sample was subjected to a washing procedure with 250 mL of deionized water for 60 s. The washing solution was then first filtered through a metal sieve (Fritsch analysensieb, Idar-Oberstein, Germany) to eliminate particles larger than 100 μm and sequentially filtered using 3 filters with increasing retention capacities (type 1288, retention: 10 μm; type 391, retention: 2.5 μm; and PTFE membrane, retention: 0.2 μm) (Sartorius AG, Goettingen, Germany). Filtration was performed using a filtration apparatus equipped with a 47 mm glass filter funnel (Sartorius stedim, Sartorius AG, Goettingen, Germany) connected to an MV-50 vacuum pump (Comecta-Ivymen, Barcelona, Spain). Before filtration, the PTFE membranes were moistened with isopropyl alcohol to facilitate the process. Prior to filtration, each filter was dried at 60 °C for 30 min in a drying chamber (WTB Binder 7200, Tuttlingen, Germany) and then left to stabilize (at 50% air relative humidity) for 120 min before being pre-weighed on a high-precision balance (ED224S-OCE, Sartorius, Germany). After filtration, filters were dried again, the weight was stabilized, and then post-weighed. To consider potential balance drifts, the tare was reweighed every 15 min. The amount of PM was determined by the difference between the post-weight and pre-weight. Three fractions of PM_x were collected during the entire filtration procedure: (1) large ($PM_{10–100}$), (2) coarse ($PM_{2.5–10}$) and (3) fine ($PM_{0.2–2.5}$). The PM_{10} fraction was obtained by adding the second to the third fraction, while the $PM_{2.5}$ fraction was considered equivalent to the third fraction. After filtration, the leaf area of each sample was measured using an A3 scanner (HP OfficeJet Pro 7740, HP Development Company, L.P., Palo Alto, CA, USA) and a leaf area software (Leaf Area Measurement, version 1.3, University of Sheffield A.P., Askew, UK). The PM_x accumulation was then expressed per unit leaf area (μg cm^{-2}).

To obtain PM deposition per unit leaf area (μg cm^{-2} day^{-1}) (i.e., the change in accumulation over time), a linear trend of deposition over the accumulation measurements was assumed. Thus, deposition was calculated as accumulation divided by the number of days without rainfall since the last effective rain (i.e., the one assumed to wash off the particles from the leaves, considered here higher than 7 mm day^{-1}). Up to a maximum of 15 days from the effective rain was observed in this experiment. Thus, the amount of deposited PM_{10} ($depPM_{10}$) and $PM_{2.5}$ ($depPM_{2.5}$) was expressed per unit leaf area and time (μg cm^{-2} day^{-1}). $depPM_x$ was upscaled to PM deposition per unit crown projection area ($depPM_{x,cpa}$, g m^{-2} ground day^{-1}) as follows:

$$depPM_{x,cpa} = depPM_x \times LAI \times 10^{-2} \quad (8)$$

where 10^{-2} is the conversion factor from μg cm^{-2} to g m^{-2}.

2.4. Statistics

All statistics were performed using SPSS software (IBM SPSS Statistics for Windows, Version 29.0 Armonk, NY, USA), while figures were drawn with SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA). Data were analyzed using linear mixed models within each city, estimated using restricted maximum likelihood (REML), with denominator degrees of freedom for tests of fixed effects obtained via the Satterthwaite approximation. In the model "species", "leaf position" and "season" were considered fixed factors, while "block" was considered a random factor. A homogeneous ante-dependence correlation structure (AD1) was chosen based on the best fitting. Leaf position was not considered when analyzing benefits expressed per unit crown projection area. Only the species factor was considered for Leaf Area Index (*LAI*, m^{-2} m^{-2}). The assumptions of normality and homoscedasticity were verified by visual inspection of the diagnostic plots. Homogeneous subsets were identified using Tukey's and Sidak's post hoc tests. The growth curves *DBH*-R_{crown} and *DBH*-H_{tot} were fitted using the curve fitting tool included in SPSS. Different functions (e.g., linear, power and logarithmic functions) were tested for fitting.

3. Results

3.1. Growth Curves

Leaf Area Index (*LAI*), stem diameter and crown radius of the different species were monitored in Lugano and Bolzano. *LAI* significantly differed among species both in Lugano ($p < 0.001$) and Bolzano ($p < 0.05$) (Table 4). In Lugano, *Ee*, *Ln*, *Pt* and *Pl* showed higher *LAI* than *Fi* and *Lv*. In Bolzano, *LAI* was similar among species except for *Pl*, which showed a higher *LAI* than *Ej* (Table 4). The three species that were monitored in both cities (*Fi*, *Pt* and *Pl*) exhibited, in general, higher *LAI* in Lugano than in Bolzano ($p < 0.05$).

Table 4. For each species and experimental site, Leaf Area Index (*LAI*, m^2 m^{-2}) values are shown, along with parameters (scaling constant (a) and exponenet (b)) and coefficient of determination (R^2) of the regression curves ($Y = a X^b$) describing the relationships between stem diameter at 30 cm height (D_{30}, m) and crown radius (R_{crown}, m), and between D_{30} and total plant height (H_{tot}, m). In the LAI column, different letters indicate significant differences among species.

				$R_{crown} = a \times D_{30}{}^{b}$			$H_{tot} = a \times D_{30}{}^{b}$		
	Species	***LAI* (m^2 m^{-2})**		**a (m)**	**b**	**R^2**	**a (m)**	**b**	**R^2**
Lugano	*Elaeagnus* × *ebbingei*	5.60	a	4.182	0.604	0.375	6.839	0.573	0.579
	Forsythia × *intermedia*	3.73	b	8.335	0.455	0.139	8.335	0.455	0.139
	Laurus nobilis	4.20	ab	4.300	0.675	0.523	10.167	0.633	0.518
	Ligustrum vulgare	3.39	b	5.088	0.684	0.429	1.912	0.007	0.000
	Pittosporum tobira	4.63	ab	4.065	0.699	0.552	12.122	1.044	0.568
	Prunus laurocerasus	5.80	a	7.886	1.017	0.619	9.231	0.711	0.483
Bolzano	*Deutzia scabra*	3.38	ab	10.646	0.975	0.687	9.142	0.564	0.275
	Euonymus japonicus	3.07	b	10.270	0.955	0.938	7.519	0.561	0.802
	Forsythia × *intermedia*	3.54	ab	6.710	0.684	0.218	5.201	0.31	0.058
	Pittosporum tobira	3.83	ab	4.164	0.582	0.215	7.681	0.592	0.409
	Prunus laurocerasus	4.50	a	4.749	0.693	0.588	8.966	0.635	0.703
	Viburnum tinus	3.94	ab	3.749	0.582	0.623	20.684	0.912	0.747

D_{30} and species were significant predictors of the crown radius (R_{crown}) ($p < 0.001$). The best fitting between D_{30} and R_{crown} was obtained in both cities using a power function ($R_{crown} = a \times D_{30}{}^{b}$) with average R^2 of 0.439 and 0.545 in Lugano and Bolzano, respectively (Table 4). D_{30} and species were significant predictors of plant height (H_{tot}) ($p < 0.001$). The

power function (H_{tot} = a × D_{30} ^{b}) best-fitted the observed data in all species with an average R^2 of 0.381 and 0.499 in Lugano and Bolzano, respectively. The specific coefficient values and R^2 of both regressions, categorized by species and city, are shown in Table 4.

3.2. CO_2 Assimilation

3.2.1. CO_2 Assimilation per Unit Leaf Area

Photosynthesis of the different species was measured in sun and shaded leaves in Lugano and in Bolzano, during the different seasons. In Lugano, the net CO_2 assimilation per unit leaf area (A_{leaf}, µmol m^{-2} s^{-1}) significantly differed among species, seasons and leaf positions ($p < 0.001$). *Fi* and *Ee* showed higher A_{leaf} than *Ln*, *Lv*, and *Pl*. *Pl* had significantly lower A_{leaf} compared to all the other species investigated (Figure 1A). Apical external leaves (ae) had 6.94% higher A_{leaf} than basal external leaves (be). Shaded apical and basal leaves (ai and bi) had 60% and 83.2% lower A_{leaf}, respectively, compared to ae (Figure 1C). A_{leaf} declined in all species from spring to summer (−16.16%) and recovered in fall (+21.3% compared to summer) (Figure 1E).

In Bolzano, A_{leaf} was significantly affected by species and leaf position ($p < 0.001$) but not by season ($p = 0.241$). *Fi* and *Pt* showed higher A_{leaf} than all the other species investigated. *Pl* showed lower A_{leaf} than all the other species except for *Ej* (Figure 1B). A_{leaf} was similar in ae and be leaves. Ai and bi leaves had 51.7% and 77.5% lower A_{leaf} compared to ae (Figure 1D). Full data of A_{leaf} for each species, leaf position, season, and city can be found in Table A2 in Appendix A.

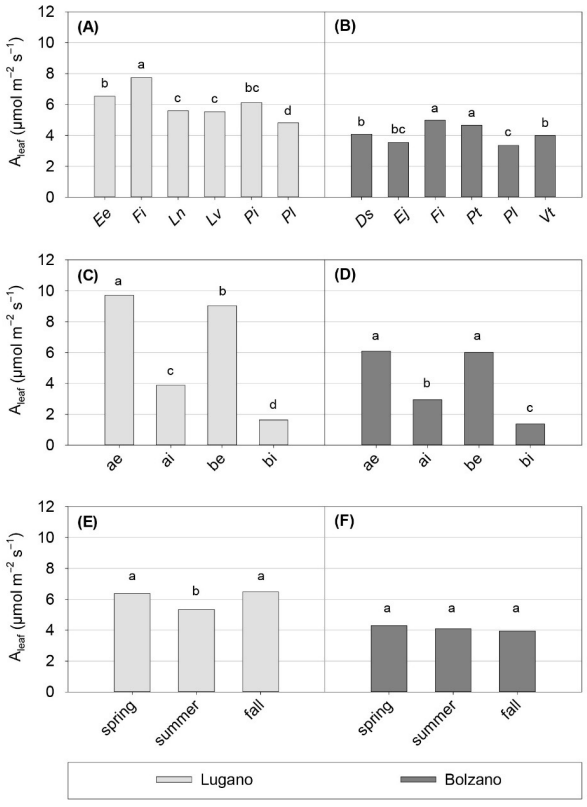

Figure 1. CO_2 assimilation per unit of leaf area (A_{leaf}, µmol CO_2 m^{-2} s^{-1}). Panels (**A**,**B**) show the effect of species, panels (**C**,**D**) show the effect of the leaf position on the crown, while panels (**E**,**F**) show the effect of season on the experimental cities of Lugano (**A**,**C**,**E**) and Bolzano (**B**,**D**,**F**). Within each panel, different letters indicate significant differences among species (**A**,**B**), among leaf positions (**C**,**D**) and between seasons (**E**,**F**) at $p \leq 0.05$. *Ds*: *Deutzia scabra*, *Ee*: *Elaeagnus* × *ebbingei*, *Ej*: *Euonymus japonicus*, *Fi*: *Forsythia* × *intermedia*, *Ln*: *Laurus nobilis*, *Lv*: *Ligustrum vulgare*, *Pl*: *Prunus laurocerasus*, *Pt*: *Pittosporum tobira*, *Vt*: *Viburnum tinus*.

3.2.2. CO_2 Assimilation per Unit Canopy Cover

In Lugano, the net hourly CO_2 assimilation per unit crown projection area at saturating irradiance (A_{cpa}, g m^{-2} ground h^{-1}) was significantly affected by species ($p < 0.001$). Season ($p = 0.089$) and the interaction between species and seasons ($p = 0.948$) were not significant. *Ee*, *Fi*, and *Pt* had higher A_{cpa} than *Lv* (Figure 2A). A_{cpa} was about 14.3% higher in spring than in summer (Figure 2C).

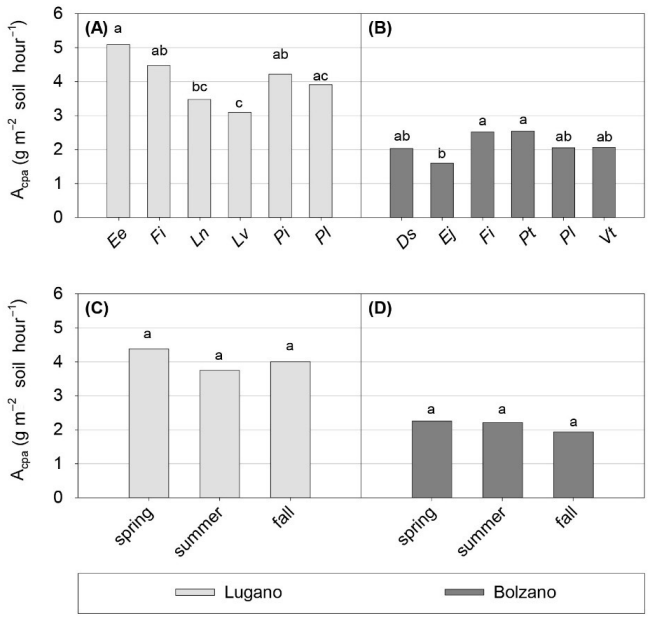

Figure 2. CO_2 assimilation per unit of crown projection area (A_{cpa}, g m^{-2} h^{-1}). Panels (**A**,**B**) show the effect of species, while panels (**C**,**D**) show the effect of season, in the cities of Lugano (**A**,**C**) and Bolzano (**B**,**D**). Within each panel, different letters indicate significant differences between species (**A**,**B**) and between seasons (**C**,**D**) at $p \leq 0.05$. *Ds*: *Deutzia scabra*, *Ee*: *Elaeagnus* × *ebbingei*, *Ej*: *Euonymus japonicus*, *Fi*: *Forsythia* × *intermedia*, *Ln*: *Laurus nobilis*, *Lv*: *Ligustrum vulgare*, *Pl*: *Prunus laurocerasus*, *Pt*: *Pittosporum tobira*, *Vt*: *Viburnum tinus*.

In Bolzano, A_{cpa} was affected by species ($p < 0.001$), while season ($p = 0.122$) and the season × species interaction were not significant ($p = 0.506$). *Fi* and *Pt* displayed higher A_{cpa} compared to *Ej* (Figure 2B). A_{cpa} was about 13.8% higher in spring and summer than in fall (Figure 2D).

CO_2 assimilation per plant during an hour of saturating sunlight irradiance, calculated as the product of A_{cpa} and *CPA*, varied between 6.18 and 41.42 g $plant^{-1}$ h^{-1} in Lugano and between 4.29 and 18.15 g $plant^{-1}$ h^{-1} in Bolzano (Table 5).

3.3. Latent Heat Dissipation

3.3.1. Transpiration per Unit of Leaf Area

Transpiration and stomatal conductance of sun and shaded leaves of the different species were measured in different seasons in Lugano and in Bolzano. In Lugano, transpiration per unit leaf area (E_{leaf}, mmol H_2O m^{-2} s^{-1}) was significantly affected by species, leaf position and season ($p < 0.001$). *Fi* displayed higher E_{leaf} than the other species evaluated (Figure 3A). *Pl* was the species with lower E_{leaf} and transpired 42.8% less water than *Fi*. All species experienced a temporary slight drop in E_{leaf} during summer (−14.9% compared to spring), then E_{leaf} fully recovered during fall. The interaction between species and leaf position was not statistically significant ($p = 0.094$).

In Bolzano, E_{leaf} was significantly affected by species, leaf position and season ($p < 0.001$). *Fi* showed 33% higher E_{leaf} than *Pl*. E_{leaf} of *Vt* and *Pt* did not differ from *Fi*. E_{leaf} increased by 42.8% from spring to summer, then dropped by 40.2% during fall

(Figure 3D). The interaction between the leaf position and the seasons was significant ($p = 0.01$).

Table 5. Average crown projection area (CPA_{avg}, m^2) and net CO_2 assimilation per plant (A_{plant}, g $plant^{-1}$ h^{-1}) of the species investigated in Lugano and Bolzano.

		CPA_{avg}	A_{plant}
Lugano	**Species**	**m^2**	**g $plant^{-1}$ h^{-1}**
	Elaeagnus × ebbingei	5.35	27.29
	Forsythia × intermedia	9.25	41.42
	Laurus nobilis	4.65	16.21
	Ligustrum vulgare	1.99	6.18
	Pittosporum tobira	6.19	26.15
	Prunus laurocerasus	4.87	19.10
Bolzano	**Species**	**m^2**	**g $plant^{-1}$ h^{-1}**
	Deutzia scabra	3.35	6.84
	Euonymus japonicus	8.06	12.96
	Forsythia × intermedia	3.10	7.84
	Pittosporum tobira	7.11	18.15
	Prunus laurocerasus	6.22	12.81
	Viburnum tinus	2.36	4.89

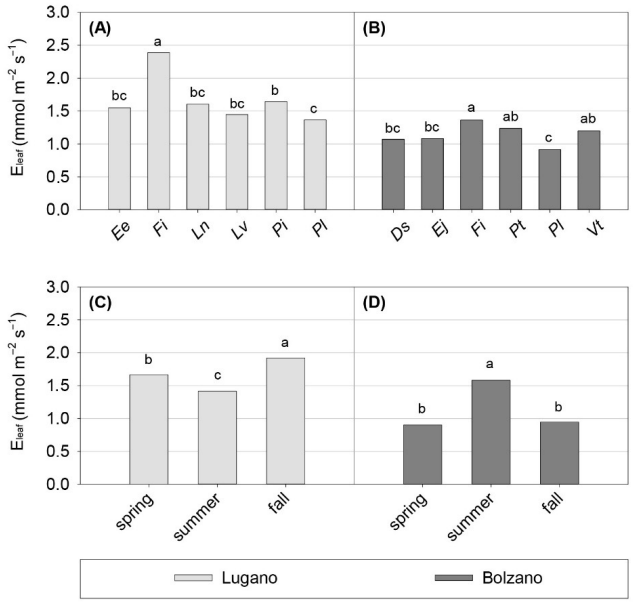

Figure 3. Transpiration per unit of leaf area (E_{leaf}, mmol m^{-2} s^{-1}) and latent heat dissipation per unit of crown projection area (LH_{cpa}, W m^{-2}). Panels (**A**,**B**) show the effect of species, while panels (**C**,**D**) show the effect of season, in the experimental cities of Lugano (**A**,**C**) and Bolzano (**B**,**D**). Within each panel, different letters indicate significant differences among species (**A**,**B**) and between seasons (**C**,**D**) at $p \leq 0.05$. *Ds*: *Deutzia scabra*, *Ee*: *Elaeagnus × ebbingei*, *Ej*: *Euonymus japonicus*, *Fi*: *Forsythia × intermedia*, *Ln*: *Laurus nobilis*, *Lv*: *Ligustrum vulgare*, *Pl*: *Prunus laurocerasus*, *Pt*: *Pittosporum tobira*, *Vt*: *Viburnum tinus*.

3.3.2. Latent Heat Dissipated per Unit Canopy Cover

In Lugano, the latent heat dissipated per unit crown projection area (LH_{cpa}, W m^{-2}) was significantly affected by the species ($p < 0.005$) and season ($p < 0.001$). The interaction between species and seasons was not significant ($p = 0.929$). *Ee* showed 27.7% higher LH_{cpa} than *Ln* (Figure 4A). LH_{cpa} was statistically similar in spring and summer, then it decreased by 32.2% in fall (Figure 4C).

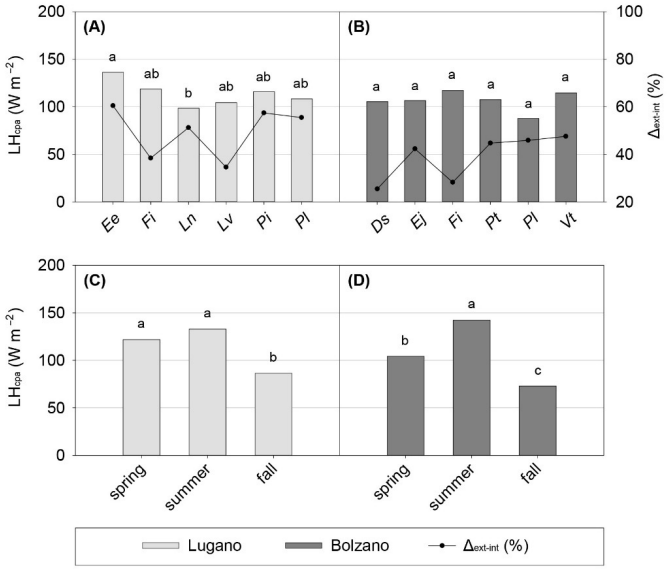

Figure 4. Latent heat dissipation per unit of crown projection area (LH_{cpa}, W m^{-2}). Panels (**A**,**B**) show the effect of species, while panels (**C**,**D**) show the effect of season, in the experimental cities of Lugano (**A**,**C**) and Bolzano (**B**,**D**). Within each panel, different letters indicate significant differences among species (**A**,**B**) and between seasons (**C**,**D**) at $p \leq 0.05$. The relative difference in LH_{cpa} between external and internal leaves across species is shown as $\Delta_{ext\text{-}int}$ (%) in panels (**A**,**B**) as a step line. *Ds*: *Deutzia scabra*, *Ee*: *Elaeagnus* × *ebbingei*, *Ej*: *Euonymus japonicus*, *Fi*: *Forsythia* × *intermedia*, *Ln*: *Laurus nobilis*, *Lv*: *Ligustrum vulgare*, *Pl*: *Prunus laurocerasus*, *Pt*: *Pittosporum tobira*, *Vt*: *Viburnum tinus*.

In Bolzano, only season significantly affected LH_{cpa} ($p < 0.001$), while species ($p = 0.088$) and the interaction between species and seasons ($p = 0.946$) did not (Figure 4B). LH_{cpa} increased by 26.7% from spring to summer, and then it dropped by 48.7% in fall (Figure 4D).

3.4. Air Quality Amelioration

3.4.1. PM Accumulation and Deposition per Unit of Leaf Area

Particulate matter accumulated on leaves of the different species growing in Lugano and Bolzano was quantified. In Lugano, species affected the accumulation of $PM_{2.5–10}$ ($p = 0.008$). *Lv* accumulated 33% more $PM_{2.5–10}$ than *Fi* and *Ln*. No significant difference was observed among species for $PM_{10–100}$ ($p = 0.160$) and $PM_{0.2–2.5}$ ($p = 0.173$) accumulation, with annual averages of 8.798 µg/cm^{-2} and 0.869 µg cm^{-2}, respectively (Figure 5A).

In Bolzano, species affected the accumulation of $PM_{10–100}$ ($p < 0.001$) and $PM_{2.5–10}$ ($p = 0.001$), while the accumulation of $PM_{0.2–2.5}$ was unaffected ($p = 0.326$). The season of sampling significantly affected the accumulation of $PM_{10–100}$ ($p = 0.042$) and $PM_{2.5–10}$ ($p < 0.001$), but did not affect the accumulation of $PM_{0.2–2.5}$ ($p = 0.096$). Evergreen species (*Ej*, *Pt*, *Pl*, and *Vt*) were 48% more efficient, on an annual basis, in $PM_{10–100}$ accumulation than deciduous species (*Ds* and *Fi*). Moreover, *Ej* was found to be 35% more effective in accumulating $PM_{2.5–10}$ than *Ds* and *Fi* (Figure 5B). No interaction was observed between species and season for the accumulation of any PM fraction in either of the two cities studied, so species were not analyzed separately by season.

Species ($p = 0.006$) and season ($p = 0.030$) affected PM_{10} accumulation in Lugano, whereas species did not affect $depPM_{10}$ ($p = 0.115$). Lower PM_{10} accumulation was observed in spring compared to winter. In contrast, $depPM_{10}$ ($p < 0.001$) was higher in spring compared to summer, when, in turn, higher $depPM_{10}$ than in fall and winter was observed (Figure 6A,B). $PM_{2.5}$ accumulation ($p = 0.749$) was unaffected by season, while $depPM_{2.5}$ was significantly higher in spring ($p < 0.001$) (Figure 6C,D).

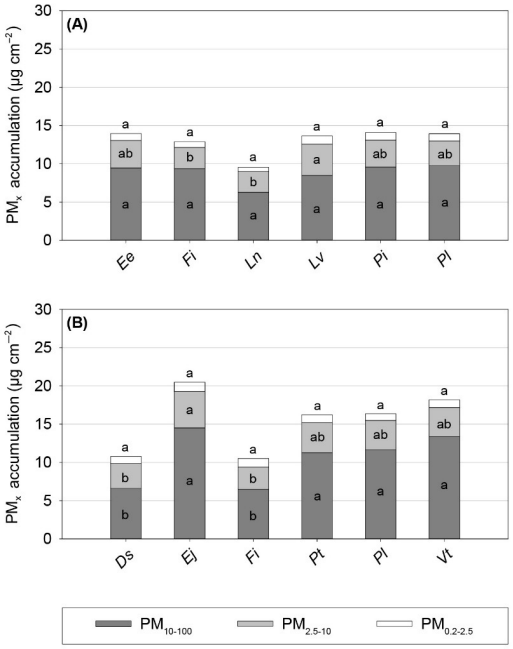

Figure 5. Effect of species on $PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$ accumulation per unit leaf area (µg cm^{-2}) in Lugano (**A**) and Bolzano (**B**). Within each PM fraction, different letters indicate significant differences among species at $p \leq 0.05$. *Ds*: *Deutzia scabra*, *Ee*: *Elaeagnus* × *ebbingei*, *Ej*: *Euonymus japonicus*, *Fi*: *Forsythia* × *intermedia*, *Ln*: *Laurus nobilis*, *Lv*: *Ligustrum vulgare*, *Pl*: *Prunus laurocerasus*, *Pt*: *Pittosporum tobira*, *Vt*: *Viburnum tinus*.

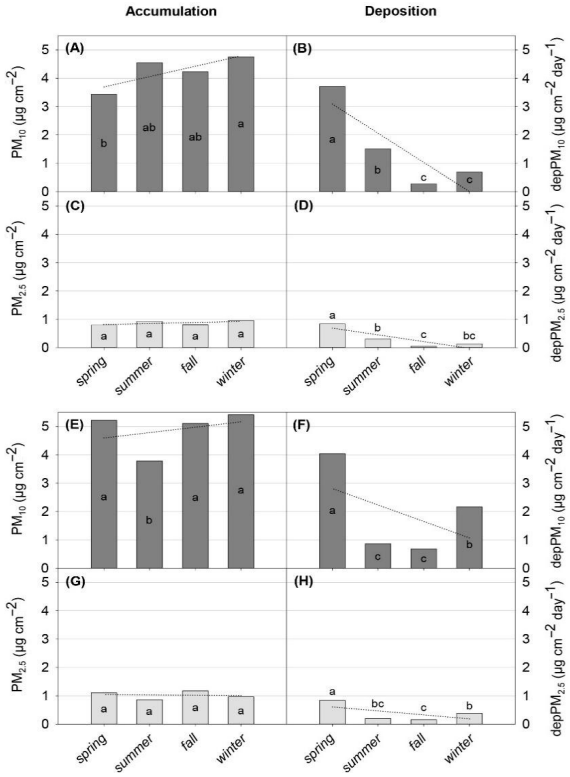

Figure 6. PM_{10} accumulation (**A**,**E**) and deposition (**B**,**F**) and $PM_{2.5}$ accumulation (**C**,**G**) and deposition (**D**,**H**) per unit leaf area in Lugano (**A**–**D**) and Bolzano (**E**–**H**). Within each variable, different letters indicate significant differences among seasons at $p \leq 0.05$. The dotted line represents the annual trend. *Ds*: *Deutzia scabra*, *Ee*: *Elaeagnus* × *ebbingei*, *Ej*: *Euonymus japonicus*, *Fi*: *Forsythia* × *intermedia*, *Ln*: *Laurus nobilis*, *Lv*: *Ligustrum vulgare*, *Pl*: *Prunus laurocerasus*, *Pt*: *Pittosporum tobira*, *Vt*: *Viburnum tinus*.

In Bolzano, the accumulations of PM_{10}, $depPM_{10}$, and $depPM_{2.5}$ were significantly affected by season ($p < 0.001$ for all traits). Species affected neither $depPM_{10}$ ($p = 0.131$) nor $depPM_{2.5}$ ($p = 0.318$). PM_{10} accumulation was lower in summer compared to all other seasons (Figure 6E). $depPM_{10}$ was higher in spring than winter, when, in turn, higher $depPM_{10}$ was observed compared to summer and fall (Figure 6F). The accumulation of $PM_{2.5}$ was unaffected by season, whereas $DepPM_{2.5}$ was higher in spring compared to other seasons (Figure 6G,H).

If total PM accumulation is compared between cities using data from the three species that were both in Lugano and Bolzano, *Pt* and *Pl* accumulated 14% more PM in Bolzano than in Lugano. Conversely, *Fi* accumulated 19% more PM in Lugano than in Bolzano.

Seasonal and annual accumulation and deposition values expressed per unit of leaf area for the different PM fractions by the six shrub species sampled in Lugano and Bolzano are provided in Appendix A.

3.4.2. PM Deposition per Unit Canopy Cover

In Lugano, PM_{10} deposition per unit crown projection area ($depPM_{10,cpa}$) was significantly affected by species ($p < 0.001$) and season ($p < 0.001$). *Ee* had significantly higher $depPM_{10,cpa}$ compared to *Ln*. $depPM_{10,cpa}$ was significantly higher in spring than in summer, when, in turn, higher $depPM_{10,cpa}$ was observed compared to fall and winter. $depPM_{2.5,cpa}$ was affected by season ($p < 0.001$), but was not affected by species ($p = 0.059$).

In Bolzano, species had no effect on $depPM_{10,cpa}$ ($p = 0.154$) or $depPM_{2.5,cpa}$ ($p = 0.457$). Conversely, the season significantly affected both $depPM_{10,cpa}$ and $depPM_{2.5,cpa}$ ($p < 0.001$).

Seasonal and annual deposition values expressed per unit canopy cover for both fractions by the six shrub species in Lugano and Bolzano are provided in Appendix A.

4. Discussion

4.1. CO_2 Removal from the Atmosphere

When estimated as CO_2 storage and sequestration, the capacity of shrubs to remove CO_2 is generally believed to be low, due to their small biomass at maturity [33,34]. In this research, CO_2 removal was estimated using a different approach that considers the photosynthetic capacity of the different species, as previously done with trees [4]. We conducted leaf gas exchange and Leaf Area Index measurements to calculate CO_2 assimilation per unit crown projection area (A_{cpa}). A_{cpa} is the net CO_2 uptake from the atmosphere (i.e., the photosynthetic CO_2 gain minus leaf autotrophic respiration) per unit canopy cover. Because shrubs are often planted and managed as masses rather than as individual plants, A_{cpa} may particularly be valuable for shrub species, since it provides an area-based metric for CO_2 uptake [34]. A_{cpa} of the shrub species investigated here ranged between 1.6 and 5.1 g CO_2 m^{-2} ground h^{-1}, depending on species. One m^2 ground planted with *Fi*, *Pt*, *Ee*, *Ds* removed about 40% more carbon compared to the same ground area planted with *Ln*, *Lv*, *Ej*.

The main determinants of A_{cpa} are Leaf Area Index (*LAI*) and net photosynthetic rate per unit leaf area [35]. Shrubs often display high canopy density, which can be further increased when they are regularly pruned [30,36], as it occurs in most municipalities [37]. High canopy density can result in similar *LAI* in shrubs compared to trees, although canopy height is substantially lower [36]. Consistently, shrub species investigated here displayed, on average, 10% higher *LAI* compared to tree species growing in similar climates [4]. Dense canopies with $LAI > 4.5$ were found in *Ee*, *Pl*, and *Pt*, especially when grown in Lugano, where high rainfall during sprouting may have favored shoot growth [38,39]. Increasing *LAI* enhances photosynthetic area per unit ground area, but the amount of canopy subjected to self-shading and shade intensity increases as well [35]. Plants can acclimate the morpho-

anatomy and physiology of their leaves to maintain a positive carbon balance in shade, although the capacity to acclimate depends on species and shade density [40,41]. As an example, the contribution of shaded leaves to overall canopy photosynthesis was 7% lower in Lugano than in Bolzano, because the denser canopies in the former city reduced light penetration to the inner canopy.

The contribution of shaded leaves to canopy photosynthesis did not significantly differ among species, although photosynthetic rate per unit leaf area did. *Fi*, a fast-growing deciduous species with thick palisade tissue and high chlorophyll levels [42], had higher photosynthesis per unit leaf area than most of the other species in both cities. Such a difference may be due to lower diffusive limitations to photosynthesis and to higher nitrogen allocation to the photosynthetic apparatus occurring in deciduous than in evergreen species [43]. The 37% difference in A_{leaf} observed in *Fi* between Lugano and Bolzano suggests opportunistic water use by *Fi*, which maximizes photosynthesis under high moisture availability and strictly modulates stomatal opening to avoid dehydration in drier conditions [44]. *Pt*, an evergreen heat-tolerant Mediterranean species with a more conservative water-use [44], was as effective as *Fi* for CO_2 assimilation when planted in the drier conditions of Bolzano. At the other end of the spectrum, *Pl*, a species known for its high stomatal sensitivity to moisture availability and high hydraulic limitations under water stress [45], displayed the lowest photosynthetic rate among the species investigated in both cities. The A_{leaf} values observed in this research were consistent with previous literature [45–47], although we found that A_{leaf} was, in general, lower in Bolzano than in Lugano. Such a result was unexpected, because the cities fall within the same climatic zone, but it may be due to higher soil pH in Bolzano than in Lugano and to the differing total annual rainfall and rainfall distribution between the cities. Although total rainfall was 40% lower in Bolzano than in Lugano, the latter city experienced a relatively dry summer, which did not occur in Bolzano, where summer rainfall exceeded the 30-year average by 36%.

Modeling the change in whole-plant net CO_2 assimilation as a function of plant age or stem diameter, as previously done with tree species [4], may be of little practical significance and subject to high uncertainty in shrubs for several reasons: (1) stem diameter of shrubs are seldom measured and recorded in municipal inventories [48]; (2) criteria for stem diameter measurement are often inconsistent among municipalities and tree workers, because shrubs are usually multi-stemmed and branched below 1.3 m [23]; (3) stem diameter may be a poor predictor of crown projection area and plant height in shrubs, as displayed by the low R^2 of the allometric relationship obtained here, because crown radius and height were greatly affected by planting distances, planting layout, and pruning regime [49]. On average, shrubs measured in this research assimilated 6.2 to 41.4 g CO_2 h^{-1} $plant^{-1}$ in Lugano and 4.9 to 18.2 g CO_2 h^{-1} $plant^{-1}$ in Bolzano. This is 97.8% lower than trees under a similar climate [4]. However, such a large difference between trees and shrubs is mostly due to differences in canopy size. Indeed, when estimated per square meter of canopy cover, CO_2 assimilation of shrubs accounted for 23.6% of that observed in tree species in a similar climate zone [4]. This indicates that CO_2 uptake by the urban forest can be increased by designing multi-layered green areas which integrate a shrub layer made of species with high A_{cpa}, as also suggested by [34].

4.2. Latent Heat Dissipation

Only a few studies evaluated the capacity of shrubs to improve the microclimate. Most of these studies assessed microclimate amelioration by measuring temperature using infrared or remote sensing [50,51]. In this study, latent heat dissipation (LH_{cpa}, W $m-^2$) was evaluated using a Penman–Monteith approach based on direct measurements of leaf gas exchange. LH_{cpa} by shrubs ranged between 87 and 136 W m^{-2} over the 24 h, depending

on the species. The latent heat dissipation by *Ln* was approximately one-third that of the same surface area planted with *Ee* (Figure 4A,B). Main determinants of LH_{cpa} are stomatal and aerodynamic resistances to transpiration, weather parameters and LAI.

Transpiration per unit of leaf area (E_{leaf}) differed significantly among species in both cities. *Fi* had the highest transpiration rate of the investigated species and transpired 52.3% more water than *Pl*, the species with the lowest transpiration rate. In Lugano, *Fi* outperformed other species in terms of E_{leaf}. The 54% difference in E_{leaf} observed for *Fi* between Lugano, characterized by higher total annual rainfall, and Bolzano confirms its opportunistic water use, which maximizes stomatal opening under higher water availability, but strongly regulates water loss during heat and drought stress. In contrast, *Pt*, a species characterized by a more conservative water use, showed only 14% variation in E_{leaf} between the two cities despite their different microclimatic conditions during the measurements [44]. Regardless of the city, E_{leaf} measured in this experiment were lower than those found on well-watered plants of the same species [45–47,52] and were similar to those found on *Fi*, *Ln*, *Pt* and *Vt* in studies under drought stress in pot-grown plants [46,53].

The results of this experiment indicate how differences in *LAI* and canopy density among species can affect cooling capacity. Transpiring leaf area per ground square meter increases indeed with *LAI*, with positive effects on cooling. Thus, species with high *LAI*, such as *Ee*, were extremely effective in cooling, although their E_{leaf} was relatively low. Conversely, low *LAI* prevented *Fi* from providing higher LH_{cpa} than most of the other species, despite its higher E_{leaf}. On the other hand, light transmittance to the inner canopy decreases with increasing *LAI*, thus increasing the relative amount of leaves subjected to self-shading while decreasing the irradiance reaching shaded leaves (Appendix A). As a consequence, shaded leaves of the high-*LAI* species *Ee* transpired 60% less water than their full-sun counterparts, whereas transpiration of shaded leaves of the sparse-canopy low-*LAI* *Lv* was only 34% lower than full-sun leaves.

LH_{cpa} increased with temperature and vapor pressure deficit (*VPD*), being higher in summer and lower in fall. This underlines the high potential for cooling of shrubs, which were capable of higher latent heat dissipation when it is more beneficial to the population. Apart from temperature, the drop of LH_{cpa} in fall may be associated with a higher frequency of self-shaded leaves within the canopy, due to wider solar zenith angle.

Schwaab et al. [54] showed how green spaces with trees cool down 2–4 times more than treeless green spaces. Latent heat fluxes around 100–200 W m^{-2} are reported in the literature for urban trees, measured both with direct [30,55] and indirect [56] methods. We show here that the latent heat flux by the shrub species investigated was in the same order of magnitude as that of trees. Thus, although shrubs are much less effective at casting shade than trees, because of their smaller size [30], their capacity to dissipate latent heat through transpiration should not be underestimated.

4.3. Particulate Matter Removal

Although bark contributes to PM capture, leaves are the main plant organs responsible for atmospheric PM accumulation [57]. Leaf micromorphological traits, such as trichomes, stomata, and epicuticular waxes, are often linked to higher PM retention [58–60]. Baraldi et al. [61] used Scanning Electron Microscopy to examine *Ligustrum* spp., revealing peltate trichomes, waxes, and cuticular characteristics (ridges, grooves, prominent stomata, and irregular wax deposits), which may explain the higher $PM_{2.5–10}$ and PM_{10} accumulation observed in *Lv* in Lugano. In the same study [61], *Ln* showed a stomatal density similar to *Ligustrum* spp. (200–300 stomata per mm^2) but lacked trichomes. While higher stomatal density is generally linked to greater PM adsorption on leaves [62], the absence of additional contributing factors in *Ln* may explain its low PM accumulation in Lugano. This trend

was also confirmed by other studies, where *Ln* was among the least efficient species in capturing PM [63]. *Ee*, which showed intermediate $PM_{2.5–10}$ and PM_{10} accumulation in Lugano, was identified by Mori et al. [63] as the most efficient species in PM capture due to high leaf area, biomass, and favorable leaf traits like trichomes [6]. *Fi* was among the least efficient species for $PM_{2.5–10}$ and PM_{10} accumulation in Lugano and also performed poorly in Bolzano, including for $PM_{10–10}$. Dzierzanowski et al. [64] found that *Fi* leaves had 2 to 8 times more waxes than other species analyzed; however, this did not significantly enhance PM retention. The potential of epicuticular waxes to trap PM depends on their chemical composition and structure, which vary depending on species [65]. Additionally, *Fi* lacks ultrastructures, such as thin films and tubules, that promote PM accumulation [65], potentially explaining its low efficiency observed in this study.

Macroscopic leaf properties (e.g., shape and size) and canopy structure can impact leaf PM accumulation capacity [60,66], interacting with climatic and environmental factors [67]. Leaf density within the canopy also significantly affects PM adsorption. In Lugano, *Lv* had the highest PM accumulation but the lowest LAI (33% below the average of other species). Such a result may be explained by the micro-turbulence generated in porous canopies, which can enhance $PM_{2.5–10}$ and PM_{10} capture. Canopy density influences wind turbulence, a key factor for PM deposition, especially fine particles [68]. Excessive leaf density reduces canopy porosity, limiting airflow and consequently its filtering effect [69,70]. Similarly, in Bolzano, *Ej*, which had 20% lower *LAI* than the other species analyzed, showed high accumulation of $PM_{10–100}$, $PM_{2.5–10}$, and PM_{10}. As with *Lv* in Lugano, higher canopy porosity in *Ej* likely enhanced PM capture.

Evergreen species capture PM throughout the year, including winter when air PM levels are higher, unlike deciduous species that shed their leaves annually. However, since evergreens retain their leaves for years, they may accumulate less new particulate matter each season [58,71]. In Bolzano, *Vt* was highly efficient in capturing $PM_{10–100}$ per unit of leaf area, consistently with previous research [63]. This efficiency is likely due to its abundant wax layer [61] and a dense trichome indumentum, which enhances PM retention.

Comparing the cumulative adsorption of the three species grown in both Lugano and Bolzano with the atmospheric PM concentrations during the sampling and pre-sampling periods in both cities, some trends emerged. The use of evergreen species such as *Pt* may be particularly effective in sites where air PM concentration peaks during winter, as was the case in Bolzano. In contrast, deciduous species can be used effectively when the peak in air PM concentration occurs during the growing season, such as in Lugano.

Meteorological and environmental factors can influence the complex process of accumulation, wash-off and re-suspension of PM [72,73]. In both Lugano and Bolzano, PM_{10} accumulation increased over the year, coherently with previous studies [74,75]. This is probably linked to higher winter air PM concentrations, primarily due to heating-related combustion. High winter accumulation is also attributed to wet leaf surfaces and fog, which favor wet deposition [76,77]. While high pollution levels can promote leaf PM accumulation [78,79], heavy rain and strong winds can wash off or resuspend accumulated PM [80]. In Bolzano, summer rain corresponded to the lowest leaf accumulation, while in Lugano, spring rainfall likely washed away PM, explaining lower accumulation in that season. The high PM accumulation on leaves observed in Bolzano can be explained by the dominance of evergreen species in the sample, which capture PM year-round, and by much less rainfall experienced by that city during spring, compared to Lugano [81]. Deciduous species, which shed leaves, tend to capture less PM and, among them, those that retain their leaves for longer periods are more efficient.

The opposite seasonal trend of accumulation and deposition (both per unit of leaf area and per unit canopy cover) supports the idea that particulate matter is primarily adsorbed

onto specific leaf microstructures (e.g., cuticular characteristics, trichomes, glands, etc.) [59]. As these microstructures become saturated, the deposition rate decreases [82], resulting in fewer particles that can accumulate daily on leaf surfaces that are nearing saturation.

4.4. Limitations

In this research, net photosynthetic rate, stomatal conductance and PM accumulation measured per unit leaf area were upscaled to calculate the benefits provided by some shrub species. We independently measured photosynthesis and stomatal conductance in sun and shaded leaves to upscale the data using a sun–shade model, which is more accurate than the traditional big-leaf model [12]. Nonetheless, we are aware that the estimation of CO_2 assimilation and latent heat dissipation per unit crown projection area relies on strong assumptions in the upscaling procedure. Similarly, the methods to calculate the PM deposition relied on the assumption that a rainfall event with intensity >7 mm could completely wash off PM from leaves.

5. Conclusions

This research shows that, although their benefits per plant are inextricably lower than in tree species because of smaller size, shrubs can provide significant ecosystem services in terms of CO_2 assimilation, latent heat dissipation, as well as accumulation and deposition of atmospheric particulate matter (PM). Per m^2 of crown projection area, shrubs dissipated up to 130 W m^{-2} latent heat per day and assimilated up to 5 g CO_2 m^{-2} ground h^{-1} of full sun, which can be comparable to tree species. Moreover, shrubs were efficient filters for particulate matter due to their growth form, indicating possible benefits of planting them near roads, one of the most significant emission sources. Nonetheless, the provision of such benefits varies between species, emphasizing the need for a science-based design of urban vegetation that takes into account the capacity of a given species to provide the desired benefit.

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Abbreviations

The following abbreviations are used in this manuscript:

ae	Apical external leaves
ai	Apical internal leaves
A_{cpa}	Net hourly CO_2 assimilation per unit crown projection area
A_{leaf}	Net CO_2 assimilation per unit leaf area
A_{plant}	Net hourly CO_2 assimilation by an individual plant
be	Basal external leaves
bi	Basal internal leaves
CPA	Crown projection area
D_{30}	Stem diameter measured at 30 cm height
D_{tot}	Cumulated stem diameter of multi-stemmed plants
E_{leaf}	Transpiration per unit leaf area
ES	Ecosystem services
g_s	Stomatal conductance to water vapor
LAI	Leaf Area Index
LAI_{sun}	Fraction of LAI exposed to full sun at a given solar zenith angle
LAI_{shade}	Fraction of LAI subjected to self-shading at a given solar zenith angle
LH_{cpa}	Latent heat dissipation
PAI_e	Effective Plant Area Index
PAR	Photosynthetic active radiation
PAR_{sun}	PAR experienced by external leaves
PAR_{shade}	PAR experienced by internal leaves
PM	Particulate matter
R_{crown}	Crown radius
WAI	Woody Area Index
θ	Solar zenith angle
Ω	Clumping index

Appendix A

- LAI partitioning into the sun and shade fraction

According to the multilayer approach, the crown was divided into two layers: sunny leaves and shaded leaves [29]. These two layers were again divided into two groups, apical and basal, assuming the equal vertical distribution of leaves in the crown. The *LAI* was also partitioned into its two sun and shaded fractions.

$$LAI_{sun\_a} = 2\cos\theta \times (1 - e^{-0.5 \times \Omega \times (LAI/2)/\cos\theta})$$

$$LAI_{sun\_b} = 2\cos\theta \times (1 - e^{-0.5 \times \Omega \times (LAI/2)/\cos\theta})$$

$$LAI_{shade\_a} = \frac{LAI}{2} - LAI_{sun\_a}$$

$$LAI_{shade\_b} = \frac{LAI}{2} - LAI_{sun\_b}$$

$$LAI = LAI_{sun\_a} + LAI_{sun\_b} + LAI_{shade\_a} + LAI_{shade\_b}$$

where θ is solar zenith angle (rad), and Ω is the clumping index, i.e., the aggregation of leaves around branches and plant crowns. Ω was considered as a single average value not varying along the vertical profile of the whole canopy and calculated according to the equation found by [29].

- Net CO_2 assimilation upscaling

Values of photosynthesis were obtained with punctual measurement, using saturating light for external leaves. To avoid overestimation, the upscaling of net CO_2 assimilation per unit of crown projection area (A_{cpa}, g m^{-2} $ground^{-1}$ h^{-1}) was limited to one hour of saturating light. In order to upscale to values per day, daily measurements were needed [4]. A_{cpa} was obtained by upscaling the net CO_2 assimilation per unit leaf area to the whole crown using a multilayer approach [4] on a daily basis, as follows:

$$A_{cpa\_hour} = [0.5 \times (A_{ae} \times LAI_{sun\_a} + A_{ai} \times LAI_{shade\_a}) + 0.5 \times (A_{be} \times LAI_{sun\_b} + A_{bi} \times LAI_{shade\_b})] \times 44 \times 10^{-6} \times 3600$$

where A_{cpa_hour} is the total net CO_2 assimilation by the leaves covering a square meter of crown area, respectively, during one hour of saturating light. A_{ae}, A_{ai}, A_{be} and A_{bi} are the net CO_2 assimilation per unit leaf area (µmol m^{-2} s^{-1}) of ae, ai, be and bi leaves, respectively, in spring, summer and fall (see Table A2 for full data). LAI_{sun} and LAI_{shade} are the fractions of *LAI* fully exposed to solar irradiance and self-shaded, respectively, assessed on a daily basis for each season; 0.5 is a coefficient for considering an equal distribution of leaf area between the apical and basal canopy layers; 44 * 10^{-6} is a coefficient to convert CO_2 from µmol to g, while 3600 represents the number of seconds in one hour.

- Latent heat dissipation through transpiration

The latent heat flux due to transpiration λT_c (W m^{-2}) was calculated on a daily basis, according to [31]

$$\lambda Tc = \frac{\Delta Q + \rho_a C_p \frac{VPD}{R_a}}{\Delta + \gamma\left(1 + \frac{R_s}{R_a}\right)}$$

where Q (available energy) = R_n (mean net radiation) − G (soil heat flux); ρ_a is the mean air density at constant pressure; C_p is the specific heat of air; and Δ represent the slope of the saturation vapor pressure–temperature relationship, calculated as:

$\Delta = 4098\left(0.6108\, e^{(17.27\ T)/(T+237.3)}\right)/(T+237.3)^2$ where T is the air temperature (FAO); γ is the psychrometric constant γ (kPa °C) $= 0.665 * 10^{-3} * P$, where P is the air pressure (kPa); *VPD* is the vapor pressure deficit of the air (kPa); R_a is the aerodynamic resistance and R_s is the surface resistance.

R_a can be described as the resistance from the vegetation upward and involves friction from air flowing over vegetative surfaces. R_a was calculated between the top of the trees and a reference point (z) where the measurements of weather variables were carried out according to Rana et al. [31]. This method introduces two simplifying assumptions regarding the homogeneity of the transpiration layer: R_a was assumed to be the same for the whole tree canopy and for all trees of the same species.

$$R_a = \frac{\log\left(\frac{z-d}{z_0}\right)\log\left(\frac{z-d}{h_t}\right)}{k^2 u_z}$$

where d (m) is the zero-plane displacement and is estimated as $d = 0.67h_t$; h_t (m) is the mean height of trees; k is the von Kármán constant (0.40); Uz is the wind speed (m s^{-1}), measured at the reference point z above the canopy; and z_0 (m) is the roughness length estimated by $z_0 = 0.1$ ht.

The methods used for canopy resistance (R_s) parametrization differed from Rana et al. [31]. R_s represents the resistance of vapor flow through the transpiring vegetation, hence through stomata opening, and it can also be perceived as the inverse of the canopy conductance $(1/g_{s,canopy})$.

The unit of measure of g_{sw} is converted from mmol m^{-2} s^{-1} to ms^{-1}. Therefore, the canopy conductance $(g_{s,canopy})$ is estimated for each canopy layer (sun/shade and apical/basal), upscaling the leaf stomatal conductivities (g_{sw_ai}, g_{sw_ae}, g_{sw_bi}, g_{sw_be}, mmol m^{-2} s^{-1}) with its specific *LAI* fraction (LAI_{sun_a}, LAI_{sun_b}, LAI_{shade_a} and LAI_{shade_b}; 2.3.1). R_s was obtained, for each fraction, as: $R_s = 1/g_{s,canopy}$. LH_{cpa_day} is then obtained with equation 1 using these within-fraction values. This process is repeated using the environmental condition and the leaf stomatal conductivity measured at night (LH_{cpa_night}). Finally, LH_{cpa} is calculated as:

$$LH_{cpa} = LH_{cpa\_day} + LH_{cpa\_night}$$

$$LH_{cpa\_day} = LH_{sun\_a\_day} + LH_{shade\_a\_day} + LH_{sun\_b\_day} + LH_{shade\_b\_day}$$

$$LH_{cpa\_night} = LH_{sun\_a\_night} + LH_{shade\_a\_night} + LH_{sun\_b\_night} + LH_{shade\_b\_night}$$

Table A1. The table reports the PAR values measured on apical and basal external ("ae" and "be") and internal ("ai" and "bi") leaves in Lugano (**a**) and Bolzano (**b**). The crown transmittance (τ), calculated as PARin/PARout, is separately reported for apical (τ_a) and basal (τ_b) leaves.

(**a**)

Lugano		***Elaeagnus* × *ebbingei***	***Forsythia* × *intermedia***	***Laurus nobilis***	***Ligustrum vulgare***	***Pittosporum tobira***	***Prunus laurocerasus***
Spring	ae	1297.25	1294.44	1300.13	1298.25	1296.67	1293.33
	ai	406.63	561.44	385.50	492.75	378.11	356.44
	τ_a	0.31	0.43	0.30	0.38	0.29	0.28
	be	1298.13	1300.22	1297.75	1295.00	1298.78	1299.67
	bi	74.75	90.44	142.13	178.88	87.00	50.22
	τ_b	0.06	0.07	0.11	0.14	0.07	0.04
Summer	ae	1295.63	1295.33	1299.00	1298.63	1296.89	1298.00
	ai	441.63	469.78	397.00	464.25	369.89	350.67
	τ_a	0.34	0.36	0.31	0.36	0.29	0.27
	be	1294.63	1297.89	1300.00	1299.38	1296.89	1299.78
	bi	85.00	90.56	153.25	133.50	63.11	50.11
	τ_b	0.07	0.07	0.12	0.10	0.05	0.04
Fall	ae	1296.00	1295.22	1299.38	1292.00	1295.44	1294.89
	ai	469.13	544.56	451.50	537.00	427.89	416.33
	τ_a	0.36	0.42	0.35	0.42	0.33	0.32
	be	1298.63	1300.33	1297.38	1298.38	1298.89	1296.67
	bi	85.38	101.33	165.00	151.75	72.00	54.33
	τ_b	0.07	0.08	0.13	0.12	0.06	0.04

(**b**)

Bolzano		***Deutzia scabra***	***Euonymus japonicus***	***Forsythia* × *intermedia***	***Pittosporum tobira***	***Prunus laurocerasus***	***Viburnum tinus***
Spring	ae	1298.43	1298.00	1296.14	1294.57	1294.29	1297.00
	ai	454.29	274.43	401.14	245.14	219.14	187.00
	τ_a	0.35	0.21	0.31	0.19	0.17	0.14
	be	1293.00	1295.14	1300.57	1299.14	1292.29	1300.14
	bi	175.00	90.43	156.86	86.86	56.14	83.29
	τ_b	0.14	0.07	0.12	0.07	0.04	0.06

Table A1. *Cont.*

(**b**)							
Bolzano		***Deutzia scabra***	***Euonymus japonicus***	***Forsythia × intermedia***	***Pittosporum tobira***	***Prunus laurocerasus***	***Viburnum tinus***
Summer	ae	1295.63	1298.00	1297.63	1298.38	1296.00	1297.50
	ai	395.50	304.50	322.50	277.25	239.88	268.50
	τ_a	0.31	0.23	0.25	0.21	0.19	0.21
	be	1301.63	1302.38	1298.63	1297.50	1297.63	1294.25
	bi	121.75	154.75	100.88	82.25	58.00	86.50
	τ_b	0.09	0.12	0.08	0.06	0.04	0.07
Fall	ae	1296.50	1298.50	1295.25	1294.25	1296.43	1299.88
	ai	295.00	203.25	254.38	171.63	159.71	186.88
	τ_a	0.23	0.16	0.20	0.13	0.12	0.14
	be	1296.88	1296.75	1297.75	1296.75	1297.71	1293.88
	bi	99.25	84.13	94.00	53.63	52.00	60.38
	τ_b	0.08	0.06	0.07	0.04	0.04	0.05

Table A2. The stomatal conductance to water vapor (g_{sw}; mmol H_2O m^{-2} s^{-1}) and the net CO_2 assimilation per unit of leaf area (A; µmol CO_2 m^{-2} s^{-1}) in different leaf positions and different seasons for each city. ae = apical external; be = basal external; ai = apical internal and bi = basal internal.

	gsw											
	Spring				**Summer**				**Fall**			
Lugano	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**
Elaeagnus × ebbingei	135.00	61.88	119.13	44.25	116.00	46.00	106.25	31.13	173.50	73.50	178.00	48.13
Forsythia × intermedia	229.56	134.44	201.78	102.78	132.00	112.11	149.22	59.11	215.11	140.11	205.56	131.89
Laurus nobilis	142.38	68.13	144.88	72.00	103.50	55.50	94.88	40.00	150.00	77.50	118.63	62.00
Ligustrum vulgare	98.63	80.38	104.63	67.63	95.38	51.13	70.13	45.13	137.50	94.13	102.38	71.50
Pittosporum tobira	152.56	57.00	151.22	44.22	100.44	58.89	100.44	38.67	133.78	51.89	139.22	42.78
Prunus laurocerasus	106.56	64.33	109.33	49.44	82.33	42.56	74.78	25.56	124.67	49.44	106.44	46.67
Bolzano	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**
Deutzia gracilis	63.57	65.14	66.57	47.43	49.00	43.63	59.25	42.38	81.25	81.88	89.63	71.88
Euonymus japonicus	53.86	38.00	47.86	38.14	59.75	39.63	69.88	26.13	71.63	46.00	58.75	42.00
Forsythia × intermedia	58.29	60.14	84.57	53.29	77.88	72.50	119.25	56.88	66.75	83.50	99.25	73.50
Pittosporum tobira	66.71	47.43	48.00	21.43	72.38	55.13	80.38	41.38	113.50	58.00	81.50	27.13
Prunus laurocerasus	54.57	42.43	44.86	25.71	62.63	46.38	65.25	23.75	56.71	41.86	68.29	37.14
Viburnum tinus	77.14	42.71	76.14	41.43	70.63	44.25	70.38	34.63	76.63	52.50	80.75	30.00

Table A2. *Cont.*

	A											
	Spring				**Summer**				**Fall**			
Lugano	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**
Elaeagnus × *ebbingei*	11.40	3.28	9.78	1.44	10.05	3.33	8.39	1.13	12.23	3.76	13.05	1.39
Forsythia × *intermedia*	12.42	6.41	12.39	2.57	9.86	6.02	10.99	1.32	12.41	4.97	11.14	2.46
Laurus nobilis	8.65	3.88	9.15	1.44	8.06	3.33	7.35	1.89	8.89	3.18	7.64	2.35
Ligustrum vulgare	7.74	4.51	8.28	3.09	7.41	2.95	5.51	1.78	11.01	5.71	8.19	2.33
Pittosporum tobira	10.28	3.32	10.64	1.36	8.91	3.54	8.32	1.22	10.79	3.58	9.98	1.58
Prunus laurocerasus	8.76	3.23	8.58	0.72	7.76	2.66	6.12	0.71	8.47	2.49	7.44	0.90
Bolzano	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**	**ae**	**ai**	**be**	**bi**
Deutzia gracilis	6.77	4.67	6.04	2.43	4.49	2.98	5.23	1.58	4.99	2.63	5.35	1.25
Euonymus japonicus	5.29	2.44	4.86	1.14	5.08	2.21	5.60	0.89	5.89	2.18	5.13	1.13
Forsythia × *intermedia*	5.99	4.21	7.36	2.44	7.89	3.89	9.04	1.59	5.58	3.39	6.28	1.66
Pittosporum tobira	6.76	3.16	5.14	1.23	6.83	3.60	7.03	1.48	8.81	3.08	7.06	1.06
Prunus laurocerasus	5.27	2.53	4.19	0.74	5.26	2.74	5.10	0.86	4.71	1.77	5.46	0.86
Viburnum tinus	6.73	1.69	6.57	1.43	6.05	2.18	5.43	1.13	6.41	2.58	6.24	0.84

Figure A1. Images of the experimental areas in Lugano (**right**) and Bolzano (**left**). The red perimeters identify the experimental areas: the numbers identify the plots as inventoried in the municipal tree inventory database. In Lugano, block 1 was made by plots 2004 and 2016, block 2 by 5053, block 3 by 6007 and 6024, block 4 by 8021 and 8007, block 5 by 5019, block 6 by 8009, block 7 by 5055, block 8 by 6005 and block 9 by plot 2012. In Bolzano, block 1 was made by plot 6666, block 2 by 309, block 3 by 9121 and 5077, block 4 by 4260 and 1891, block 5 by 9207, 9307 and 9211, block 6 by 3490 and 9124, block 7 by 5130, 8550 and 9001 and block 8 by plot 3103 and 9114.

Table A3. Seasonal and annual accumulation (PM_x; μg cm^{-2} leaf area) and deposition ($depPM_x$; μg cm^{-2} day^{-1}) expressed per unit of leaf area for the different PM fractions by the six shrub species in Lugano (**a**) and Bolzano (**b**).

(**a**)					
Species	**$PM_{10–100}$ (μg cm^{-2})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Elaeagnus × ebbingei	3.436	8.43	12.916	13.08	9.466
Forsythia × intermedia	5.981	8.478	13.598	-	9.352
Laurus nobilis	1.728	6.065	8.295	9.117	6.301
Ligustrum vulgare	5.109	8.565	12.469	7.778	8.48
Pittosporum tobira	5.684	8.658	12.385	11.561	9.572
Prunus laurocerasus	3.676	11.445	12.916	10.977	9.754
Species	**$PM_{2.5–10}$ (μg cm^{-2})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Elaeagnus × ebbingei	3.632	3.526	3.684	3.521	3.591
Forsythia × intermedia	2.81	2.964	2.587	-	2.787
Laurus nobilis	1.834	2.985	2.96	3.044	2.706
Ligustrum vulgare	2.833	4.307	4.629	4.583	4.088
Pittosporum tobira	2.641	3.68	3.607	4.248	3.544
Prunus laurocerasus	2.07	4.262	3.015	3.589	3.234
Species	**$PM_{0.2–2.5}$ (μg cm^{-2})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Elaeagnus × ebbingei	0.84	0.538	1.171	1.039	0.897
Forsythia × intermedia	0.876	0.7	0.702	-	0.759
Laurus nobilis	0.555	0.341	0.42	0.846	0.541
Ligustrum vulgare	0.567	1.8	0.917	1.013	1.074
Pittosporum tobira	1.137	1.056	0.683	0.999	0.969
Prunus laurocerasus	0.804	1.135	0.955	0.894	0.947
Species	**$depPM_{10}$ (μg cm^{-2} day^{-1})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Elaeagnus × ebbingei	4.893	1.362	0.310	0.641	1.802
Forsythia × intermedia	3.790	1.221	0.229	-	1.747
Laurus nobilis	2.811	1.076	0.193	0.550	1.157
Ligustrum vulgare	3.497	2.002	0.353	0.825	1.669
Pittosporum tobira	4.151	1.579	0.296	0.787	1.703
Prunus laurocerasus	3.130	1.799	0.275	0.664	1.467
Species	**$depPM_{2.5}$ (μg cm^{-2} day^{-1})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Elaeagnus × ebbingei	0.934	0.184	0.075	0.142	0.334
Forsythia × intermedia	0.89	0.233	0.048	-	0.391
Laurus nobilis	0.65	0.105	0.014	0.113	0.22
Ligustrum vulgare	0.522	0.589	0.05	0.136	0.324
Pittosporum tobira	1.209	0.352	0.047	0.152	0.44
Prunus laurocerasus	0.859	0.378	0.067	0.132	0.359

Table A3. *Cont.*

(**b**)

Species	$PM_{10–100}$ (μg cm^{-2})				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Deutzia scabra	6.629	5.265	7.929	-	6.607
Euonymus japonicus	17.195	13.369	14.745	12.723	14.508
Forsythia × intermedia	6.865	4.503	8.121	-	6.497
Pittosporum tobira	12.332	10.118	10.913	11.752	11.279
Prunus laurocerasus	9.37	9.857	15.527	11.93	11.671
Viburnum tinus	13.205	11.147	15.39	13.798	13.385
Species	$PM_{2.5–10}$ (μg cm^{-2})				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Deutzia scabra	3.585	2.556	3.662	-	3.268
Euonymus japonicus	5.5	3.469	4.787	5.235	4.748
Forsythia × intermedia	3.442	2.279	3.002	-	2.908
Pittosporum tobira	4.202	3.337	4.047	4.075	3.915
Prunus laurocerasus	3.401	3.011	4.568	4.315	3.824
Viburnum tinus	4.581	2.867	3.555	4.18	3.796
Species	$PM_{0.2–2.5}$ (μg cm^{-2})				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Deutzia scabra	0.907	0.724	1.119	-	0.917
Euonymus japonicus	1.222	1.076	1.215	1.397	1.228
Forsythia × intermedia	1.32	0.958	1.071	-	1.116
Pittosporum tobira	1.287	1.043	1.293	0.521	1.036
Prunus laurocerasus	0.733	0.538	1.16	1.052	0.871
Viburnum tinus	1.15	0.823	1.182	0.878	1.008
Species	$depPM_{10}$ (μg cm^{-2} day^{-1})				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Deutzia scabra	3.47	0.753	0.637	-	1.62
Euonymus japonicus	5.091	1.033	0.812	2.652	2.397
Forsythia × intermedia	3.631	0.755	0.55	-	1.645
Pittosporum tobira	4.167	1.007	0.716	1.816	1.927
Prunus laurocerasus	3.37	0.802	0.784	2.273	1.807
Viburnum tinus	4.522	0.833	0.629	1.928	1.978
Species	$depPM_{2.5}$ (μg cm^{-2} day^{-1})				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Deutzia scabra	0.624	0.165	0.15	-	0.313
Euonymus japonicus	0.923	0.252	0.166	0.543	0.471
Forsythia × intermedia	1.028	0.231	0.144	-	0.468
Pittosporum tobira	0.996	0.243	0.175	0.223	0.409
Prunus laurocerasus	0.607	0.12	0.157	0.431	0.329
Viburnum tinus	0.858	0.188	0.157	0.343	0.386

Table A4. Seasonal and annual deposition ($depPM_{x.cpa}$; g m^{-2} $ground^{-1}$ day^{-1}) expressed per unit of canopy cover for both fractions by the six shrub species in Lugano (**a**) and Bolzano (**b**).

(**a**)					
Species	**$depPM_{10.cpa}$ (g m^{-2} $ground^{-1}$ day^{-1})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Elaeagnus × ebbingei	0.221	0.072	0.016	0.035	0.086
Forsythia × intermedia	0.131	0.047	0.008	-	0.062
Laurus nobilis	0.117	0.045	0.008	0.023	0.048
Ligustrum vulgare	0.115	0.066	0.01	0.026	0.054
Pittosporum tobira	0.178	0.073	0.014	0.037	0.076
Prunus laurocerasus	0.195	0.11	0.017	0.038	0.090
Species	**$depPM_{2.5.cpa}$ (g m^{-2} $ground^{-1}$ day^{-1})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Elaeagnus × ebbingei	0.041	0.009	0.004	0.007	0.015
Forsythia × intermedia	0.031	0.009	0.002	-	0.014
Laurus nobilis	0.024	0.004	0.000	0.005	0.008
Ligustrum vulgare	0.017	0.02	0.001	0.004	0.010
Pittosporum tobira	0.048	0.016	0.002	0.007	0.019
Prunus laurocerasus	0.055	0.023	0.004	0.007	0.022
(**b**)					
Species	**$depPM_{10.cpa}$ (g m^{-2} $ground^{-1}$ day^{-1})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Deutzia scabra	0.109	0.027	0.022	-	0.052
Euonymus japonicus	0.164	0.033	0.027	0.083	0.077
Forsythia × intermedia	0.115	0.026	0.019	-	0.053
Pittosporum tobira	0.165	0.042	0.028	0.072	0.077
Prunus laurocerasus	0.142	0.036	0.037	0.109	0.081
Viburnum tinus	0.161	0.032	0.025	0.074	0.073
Species	**$depPM_{2.5.cpa}$ (g m^{-2} $ground^{-1}$ day^{-1})**				
	Spring	**Summer**	**Fall**	**Winter**	**Annual Average**
Deutzia scabra	0.006	0.005	-	0.006	0.010
Euonymus japonicus	0.029	0.009	0.005	0.016	0.015
Forsythia × intermedia	0.031	0.008	0.005	-	0.015
Pittosporum tobira	0.039	0.01	0.007	0.008	0.016
Prunus laurocerasus	0.027	0.005	0.008	0.019	0.015
Viburnum tinus	0.033	0.007	0.006	0.013	0.015

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