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Dry Deposition of Fine Particulate Matter by City-Owned Street Trees in a City Defined by Urban Sprawl

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Abstract

Urban expansion intensifies population exposures to fine particulate matter ($PM_{2.5}$). Trees mitigate pollution by dry deposition, in which particles settle on plants. However, city-scale models frequently overlook differences in tree species and structure. This study assesses $PM_{2.5}$ removal by individual city-owned street trees in Mississauga, Canada, throughout the 2019 leaf-growing season (May to September). Using a modified i-Tree Eco framework, we evaluated the removal of $PM_{2.5}$ by 200,560 city-owned street trees (245 species) in Mississauga from May to September 2019. The model used species-specific deposition velocities (V_d) from the literature or leaf morphology estimates, adjusted for local winds, a 3 m-resolution satellite-derived Leaf Area Index (LAI), field-validated, crown area modelled from diameter at breast height, and 1 km^2 resolution $PM_{2.5}$ data geolocated to individual trees. About twenty-eight tons of $PM_{2.5}$ were removed from 200,560 city-owned trees (245 species). Coniferous species (14.37% of trees) removed 25.62 tons (92% of total), much higher than deciduous species (85.63%, 2.18 tons). *Picea pungens* (18.33 tons, 66%), *Pinus nigra* (3.29 tons, 12%), and *Picea abies* (1.50 tons, 5%) are three key species. Conifers' removal efficiency originates from the faster deposition velocities, larger tree size, and dense foliage, all of which enhance particle deposition. This study emphasizes species-specific approaches for improving urban air quality through targeted tree planting. Prioritizing coniferous species such as spruce and pine can improve pollution mitigation, providing actionable strategies for Mississauga and other cities worldwide to develop green infrastructure planning for air pollution.

Keywords: dry deposition; $PM_{2.5}$; city-owned street trees; nature-based solutions

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1. Introduction

The urban landscape of the 21st century is marked by rapid changes, among which urban sprawl is particularly impactful [1,2]. Urban sprawl, defined as low-density and dispersed development, frequently results in segregated zoning that divides residential, commercial, and industrial districts. Consequently, public transportation alternatives are limited because of the low potential of passengers in such dispersed localities [1,3]. As a result, urban sprawl disrupts the ecosystem and exacerbates air pollution by increasing reliance on automobiles, a major contributor to traffic-related air pollution (TRAP), resulting in urban air quality degradation [4–6]. The degradation of air quality has drawn scientific attention to its health implications, particularly concerning fine particulate matter, particles 2.5 micrometres or smaller in aerodynamic diameter. Several studies have indicated an

association between $PM_{2.5}$ exposure and an increased risk of asthma attacks, cardiovascular illnesses, and premature death [7–11].

Although urgent efforts are required to reduce $PM_{2.5}$ from emission sources [12–15], emission source reductions are usually prolonged due to the complexity of controlling $PM_{2.5}$. Urban Green Infrastructure (UGI), particularly urban trees, is increasingly recognized as a cost-effective solution for improving urban environmental quality [16–19]. Among its many benefits, UGI has been widely recommended for mitigating air pollution, as trees can intercept $PM_{2.5}$ and absorb gaseous pollutants through their leaves and bark [20–24]. Understanding the specific mechanisms, such as the capture of $PM_{2.5}$, is crucial for optimizing UGI's air pollution mitigation potential. A growing body of research has investigated the capacity of different plant species to capture $PM_{2.5}$ on leaf surfaces [25–28]. $PM_{2.5}$ near the leaf surface can be pulled into the stomatal chamber and embedded in leaf hairs and wax layers over time [24,25,29–32]. Species with rougher leaf textures, such as conifers, and those with dense trichomes (hair-like structures) or thicker wax layers on their leaves, are particularly effective at intercepting $PM_{2.5}$ [24,26,27,30].

Dry deposition modelling is an ecosystem-based process that quantifies the gravitational sedimentation of atmospheric particles on urban surfaces without precipitation [33,34]. Among the various methods used to implement dry deposition modelling, the i-Tree Eco model stands out because of its comprehensive assessment capabilities for urban canopies at the city level [35–42]. To model dry deposition at the city level, the downward hourly pollution flux (g m^{-2} h^{-1}) was estimated using dry deposition velocity (V_d) and the concentration of air pollutants (C) [33].

Dry deposition studies of $PM_{2.5}$ demonstrate reductions on the scale of 4.7 tons to 64.5 tons in ten cities in the U.S., using i–Tree Eco, which used a uniform $PM_{2.5}$ deposition velocity (V_d) for all tree species within the city [43]. Using the i-Tree Eco model, studies have found that trees removed 5.4 metric tons of $PM_{2.5}$ annually from public green spaces in Strasbourg, France [44], while urban trees removed 64.5 tons of $PM_{2.5}$ in a year in Auckland, New Zealand [45]. However, dry deposition modelling studies have found that there is a seasonal effect in dry deposition using 48 street trees in Shenyang, China, or 1245 trees in 85 species Beijing and 87 species Shanghai in China [46,47]. In addition, research identifies rate changes across species depending on leaf morphology, local meteorological conditions, and pollutant concentrations surrounding trees, aerodynamic effects from tree arrangement and urban morphology [5,20–22,47,48]. Furthermore, modelling studies on a regional scale using i-Tree [43,44] often aggregate total $PM_{2.5}$ mitigation by trees across the entire region, potentially overlooking the variability in $PM_{2.5}$ reduction potential among different tree species within cities [31,43,46].

Given the highlighted variability in deposition rates and the aggregation method in regional studies, a more detailed modelling approach is necessary to quantify the species-specific contributions to $PM_{2.5}$ removal accurately. Quantifying $PM_{2.5}$ removal through dry deposition modelling involves factors such as dry deposition velocity, a critical factor determining how quickly $PM_{2.5}$ particles settle on surfaces, which varies greatly among tree species due to differences in leaf morphology and local wind conditions [4,20,21,25,32]. To date, comprehensive modelling of $PM_{2.5}$ dry deposition at the individual tree level within urban areas is lacking, leaving uncertainties regarding the species-specific contributions of $PM_{2.5}$ mitigation through dry deposition. By focusing on the specific traits of individual tree species, our proposed modelling approach aims to fill the current gap in understanding how different tree species contribute to $PM_{2.5}$ removal, overcoming the limitations of broad, regional aggregates.

This study aims to develop a scalable method for estimating the dry deposition of $PM_{2.5}$ using city-owned street trees at the individual tree level in a suburban-dominated

landscape (Mississauga, Canada). We seek to quantify $PM_{2.5}$ removal through dry deposition by coniferous and deciduous trees and all city-owned street trees during the in-leaf season (1 May to 30 September 2019). The results will model the potential $PM_{2.5}$ reductions by tree species, providing insights into targeted urban forestry strategies to improve air quality. This research contributes to urban ecology and air quality management by assessing $PM_{2.5}$ deposition at the individual tree level and evaluating the performance of different tree species in reducing air pollution. Our work supports broader sustainability objectives by mitigating the health impacts of air pollution and enhancing ecosystem health, ultimately promoting healthier urban environments in cities worldwide.

2. Methods

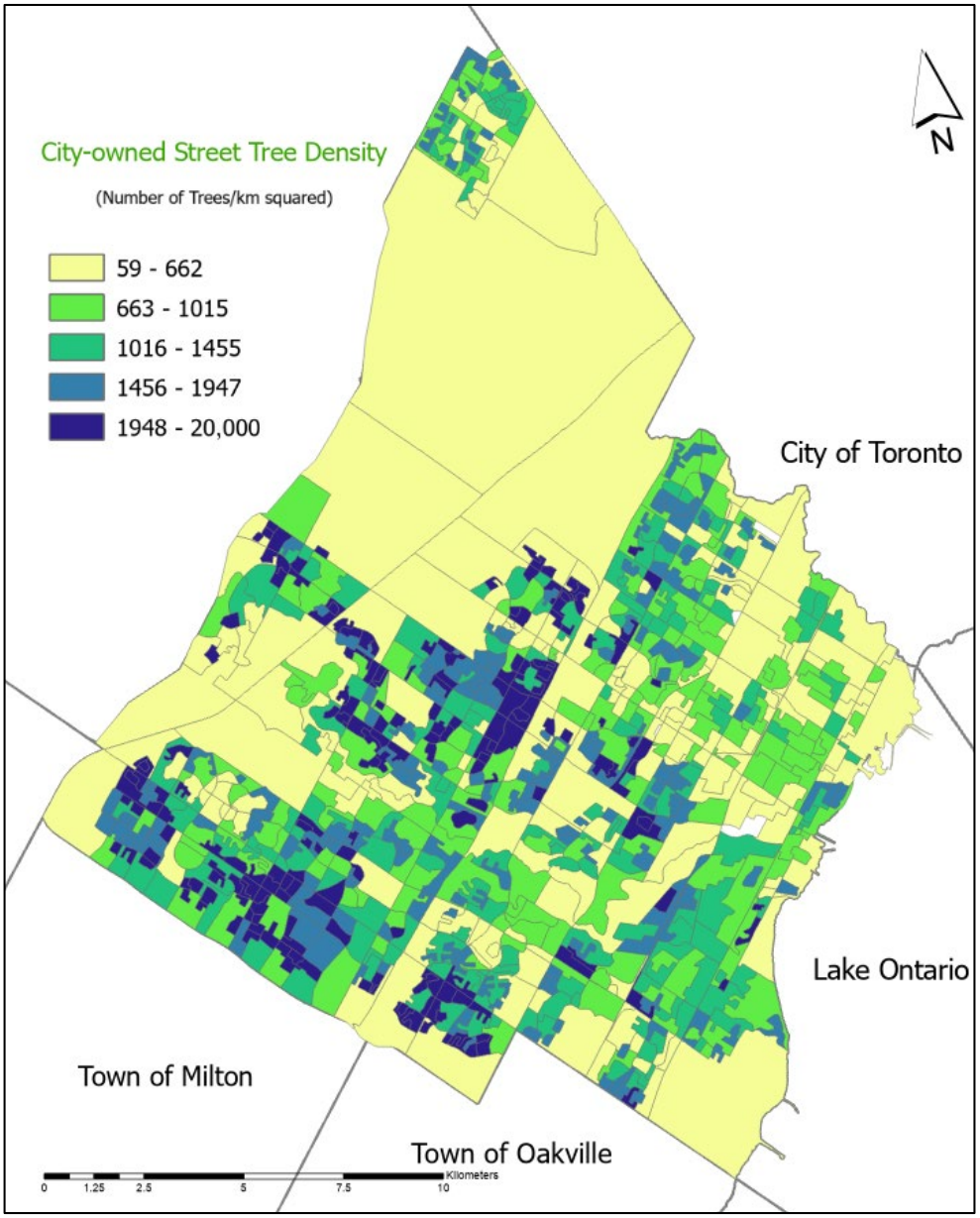
2.1. City-Owned Street Trees in Mississauga

Mississauga, Canada, the sixth-largest metropolitan area in Canada, has a population of 717,961 [49] (Figure 1a). The city is on the southern shore of Lake Ontario, experiencing a continental climate with the highest monthly temperature in July (22.5 °C) and the lowest monthly temperature in January (−4.5 °C) based on the 1991–2021 normal [50]. The city's tree inventory catalogued all city-owned trees, detailing common names, geographic locations, and diameter at breast height (DBH) (cm) [51]. Using ArcMap 10.8, we excluded trees in parks and natural areas because we would only like to consider the city-owned street trees. The study period, 1 May to 30 September 2019, was selected to coincide with active photosynthesis in coniferous and deciduous trees throughout the city [34,52]. Biological taxonomy classifications [53] of city-owned street trees were summarized for analysis.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. (**a**) Location of Mississauga, Ontario, Canada within the provincial and national contexts, and (**b**) the national and provincial context, and (**b**) spatial distribution of city-owned street tree density in Mississauga.

The City of Mississauga's tree inventory included 305,759 trees on street boulevards and parks in 2019. We removed the private trees from the inventory and trees located in the parks and natural areas using ArcMap 10.8 and retained street trees in the city. We removed dead trees, stumps, shrubs, and trees with missing species names from the tree inventory (Figure 1b). Street trees with DBH equal to zero cm and trees with DBH equal to or greater than 400 cm are removed from the analysis. A tree with a diameter of 400 cm would be considered too large to be a valid street tree in this study. The average DBH for the trees we investigated is approximately 17 cm. In urban forestry, street trees typically have a DBH of less than 100 cm. A 400 cm DBH tree is unusually large, more resembling ancient or woodland trees than planted urban street trees. Such a result could be due to a measurement error or a unique heritage specimen outside the scope of our study. We excluded it to ensure data consistency.

2.2. Dry Deposition Velocity by Tree

Plant foliage serves as a sink to immobilize particulates [54]; however, the rate of the deposition velocity depends on the tree species, type of air pollutant, concentration of ambient air pollutants, and local wind speed [33,55]. In dry deposition modelling, dry deposition velocity (V_d) is interpreted as the rate of $PM_{2.5}$ deposition during non-precipitation conditions [20–23,34]. We first obtained deposition velocities of $PM_{2.5}$ ($V_{d\ PM2.5}$, g m^{-2} h^{-1}) of ten tree species from existing literature that included *Quercus petraea*, *Fraxinus excelsior*, *Pseudotsuga menziesii*, *Scandosorbus intermedia*, *Acer pseudo-platanus*, and *Phyllostachys nigra*, which we used as reference species to characterize dry deposition of $PM_{2.5}$ at various wind speeds as seen in Supplementary Materials Table S1.

Estimation at unreported wind speeds used a linear regression model of $V_{d\ PM2.5}$ (g m^{-2} h^{-1}) against the wind speed given by the literature, which was bounded to the range of reported wind speeds in the literature from 1 to 10 m/s [20–23]. Following that, we calculated the average wind speed (m/s) for the City of Mississauga from 1 May to 30 September 2019, using hourly measurements reported from the Toronto Pearson International Airport (43°40′36″ N, 79°37′50″ W), which is located within Mississauga. We applied the average wind speed during the study period (m/s) in the city during the study period to the known values of dry deposition velocities from the literature. We estimated the V_d of the ten tree species at the local wind speed for the city during the study period.

Empirical estimates for deposition velocity are limited to a few species in the scientific literature [20–22,24,26,54]. We identified the taxonomic order of street tree species using a scientific taxonomy classification [53]. We matched city-owned street trees in Mississauga with the ten reference tree species from the literature if both species shared the same taxonomic order [20–23]. For the city's tree species that belong to the same taxonomic order as the reference species, we used the $V_{d\ PM2.5}$ of the reference tree species to calculate the deposition velocity of each city tree species. We estimated their deposition velocity using leaf shape similarities for street tree species that did not belong to an evaluated taxonomic order as the reference species (Supplementary Materials Table S3).

The dry deposition of $PM_{2.5}$ onto tree canopies depends on meteorological conditions (e.g., wind speed) and the available leaf surface area for particle interception. LAI—the one-sided leaf area per unit ground area (m^2/m^2)—quantifies canopy density and directly influences deposition efficiency. To account for this, the i-Tree Eco model computes tree-specific deposition velocity (V_d) by scaling a leaf-area-normalized deposition velocity ($V_{d\ PM2.5}$) by the tree's LAI.

The species-specific $V_{d\ PM2.5}$ were derived from empirical studies [20–23,33] and represent deposition rates per unit LAI under varying wind speeds (Supplementary Materials Table S1). LAI linearly adjusts these values to estimate total deposition per tree, assuming uniform particle capture across leaves [43]). The tree-level V_d is calculated as

$$V_d = V_{d\ PM2.5} \cdot LAI \quad (1)$$

where

V_d = deposition velocity (m/s);

$V_{d\ PM2.5}$ = deposition velocities of $PM_{2.5}$ (m/s) at the individual species level;

LAI = Leaf Area Index (m^2/m^2).

2.3. Satellite Estimates and Field Validation of Leaf Area Index

The Leaf Area Index (LAI) measures the amount of green leaf area on one side for each unit of ground area (m^2/m^2) and is important for understanding how dense a plant canopy is and how it affects $PM_{2.5}$ dry deposition [33,55,56]. Since LAI is closely related to vegetation reflectance characteristics, it can be assessed remotely through the Normalized

Difference Vegetation Index (NDVI). As LAI increases, greater chlorophyll absorption in the red band (620–670 nm) and higher reflectance in the near-infrared (NIR, 845–885 nm) enhance NDVI values [57,58]. We used 3 m-resolution PlanetScope imagery (Dove satellites) [59] from 14 July 2019, a cloud-free in-leaf date, to map LAI across Mississauga, as seen in Figure 2. In this work, the spatial measuring unit for LAI is 3 m, which corresponds to a reliable LAI estimate to reduce errors from overlapping canopies in dense urban settings, where trees are frequently planted in confined places.

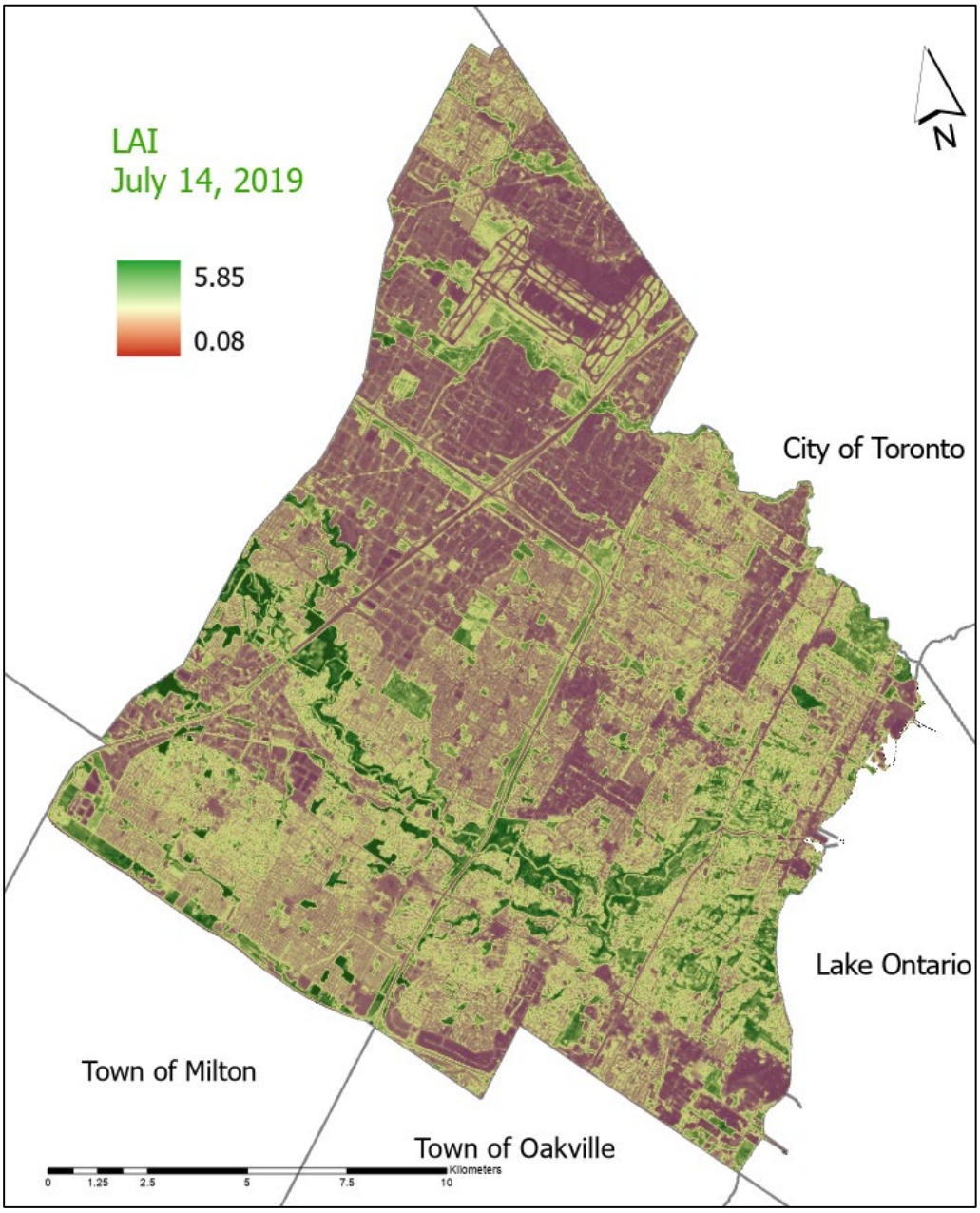


Figure 2. Satellite estimates of LAI with a resolution of 3 m × 3 m on 14 July 2019, for the City of Mississauga, Canada.

To validate the satellite-derived LAI, we conducted field measurements on 3 July 2022, for 88 street trees representing 28 common species and seven taxonomic orders in Mississauga. In 2019, the local government conducted a tree inventory. Our study aimed to estimate the $PM_{2.5}$ deposition from city-managed street trees during the leaf-on season for that particular year. Field measurements of LAI, however, were taken in 2022. LAI

was measured using hemispherical photography (Nikon Coolpix 8400 with a fisheye lens), following standardized protocols to ensure consistency with satellite resolution [60]. The camera was positioned 1.2 m above ground and 1.5 m from the trunk centre, matching the 3 m pixel scale of PlanetScope imagery. Photos were taken under overcast skies to minimize shadows and processed using TRACWin Version 1.0.3 [61]. A linear regression was used to compare field and satellite LAI values from 2022 (Figure 3) to update the 2019 estimates, considering small changes in the tree canopy while taking advantage of the stability of mature urban trees. This calibration strengthened the accuracy of LAI for $PM_{2.5}$ deposition modelling, bridging remote sensing with ground-truth data.

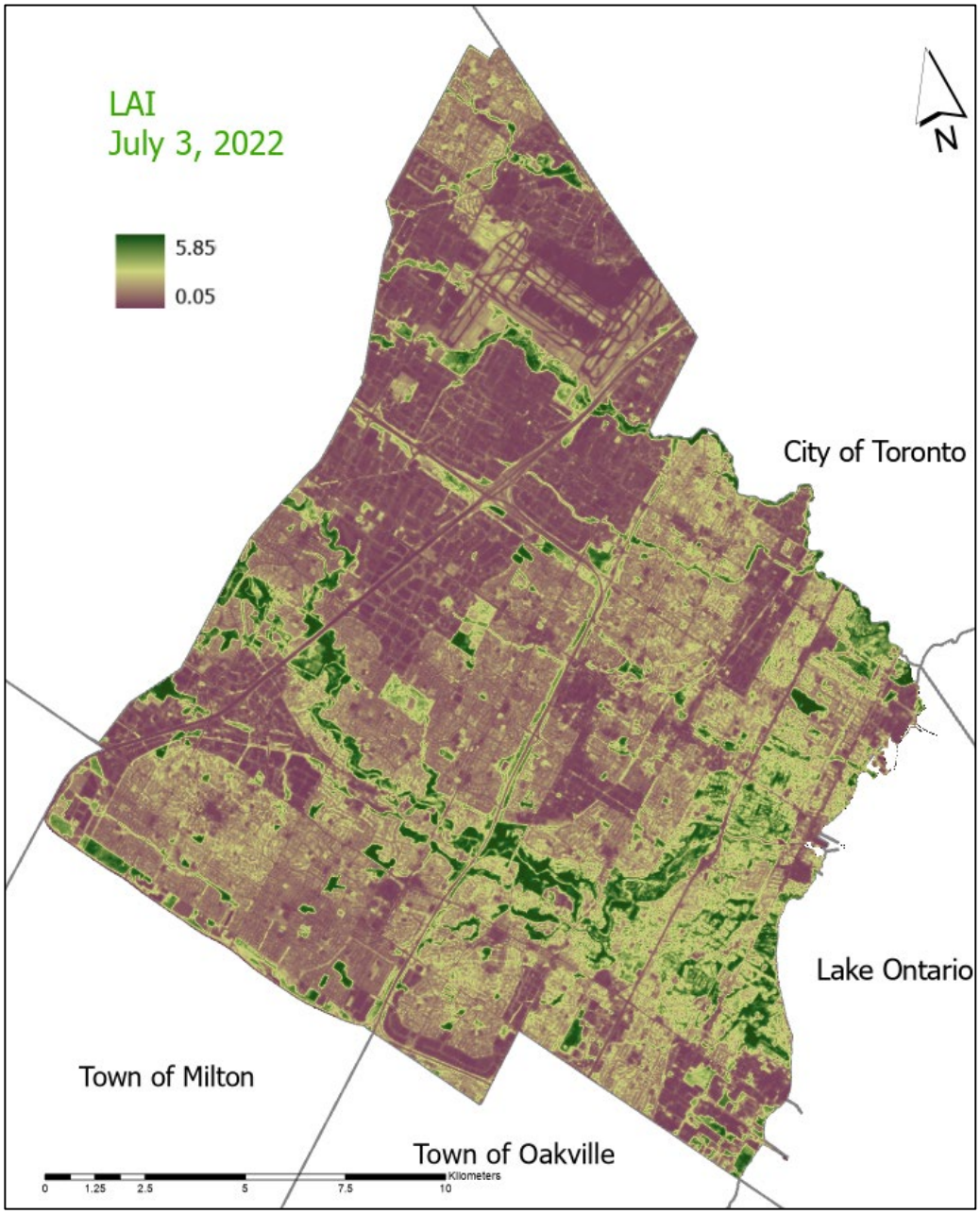


Figure 3. Satellite estimates of LAI with a resolution of 3 m × 3 m on 3 July 2022, for the City of Mississauga, Canada.

2.4. Ambient $PM_{2.5}$ Surrounding Individual Trees

Ambient $PM_{2.5}$ concentrations were obtained from the Version 5.GL.05.02 dataset [62], which provides high-resolution (1 km^2) monthly and annual average surface-level $PM_{2.5}$

estimates for 1998–2023. These estimates combine satellite data on aerosol optical depth (AOD) from NASA instruments like MODIS, MISR, SeaWiFS, and VIIRS with GEOS-Chem chemical transport model simulations. A Geographically Weighted Regression (GWR) calibrated these hybrid estimates against global ground-based $PM_{2.5}$ measurements to ensure local accuracy. For our study, we extracted warm-season (May–September 2019) $PM_{2.5}$ values, matching our investigation period, as seen in Figure 4.

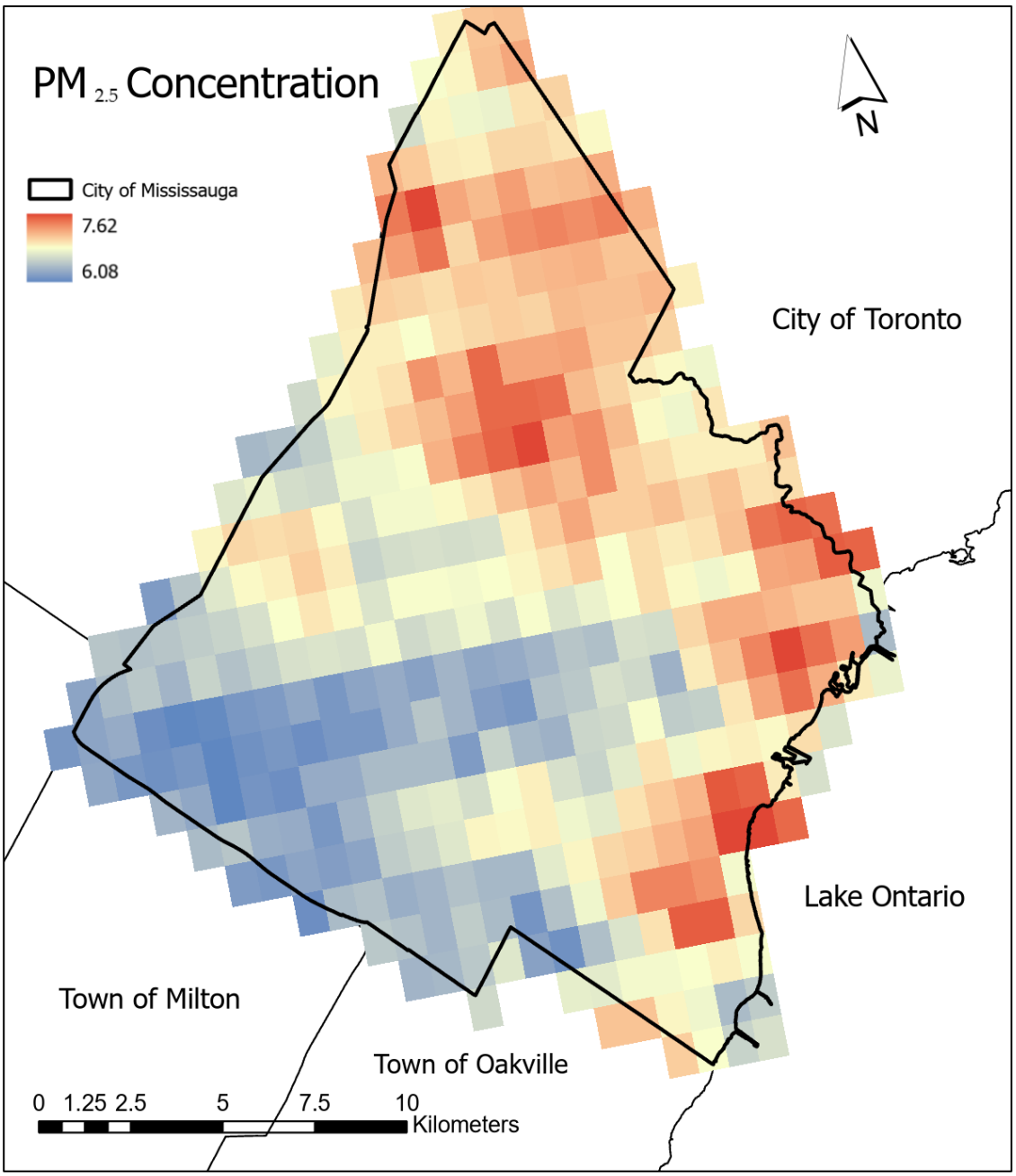


Figure 4. Ambient $PM_{2.5}$ concentration during the in-leaf season of 2019 (1 May–30 September 2019).

While the background $PM_{2.5}$ data has a 1 km^2 resolution from the highest resolution validated global dataset available, we implemented a spatial joint and precision matching process in RStudio 4.0.5 that precisely geolocated each of the 200,560 street trees using the tree inventory's coordinates to assign each tree its ambient concentration.

2.5. Area of Deposition

The dry deposition area (A), representing the crown projection area (CPA) available for $PM_{2.5}$ capture, was estimated using a simplified quadratic model based on [63]. The original power-sigmoid model relates CPA to tree diameter at breast height (DBH), capturing how CPA increases with DBH but gradually levels off as trees mature. To enable large-scale applications using available inventory data, we adopt the following simplified form:

$$A = a \times (DBH)^2 \quad (2)$$

where

A = estimated deposition area (m^2);

DBH = diameter at breast height (cm), obtained from the city's street tree inventory;

a = 0.02422 for deciduous trees; 0.0205828 for coniferous trees.

This relationship bridges basal area-based and crown area-based formulations in Shimano's power-sigmoid model [63]. Given each tree's DBH from the inventory, this equation enables direct calculation of its dry deposition area, facilitating city-wide assessments of $PM_{2.5}$ capture potential. The spatial measurement unit for the area of deposition is at the individual tree level.

2.6. Study Period

Between 1 May and 30 September 2019, there were 153 days of in-leaf season for both coniferous and deciduous trees, assuming no rain happened throughout the study period. We converted 153 days into seconds (13,219,200 s) and used Equation (3) to predict the dry deposition of $PM_{2.5}$ at the individual tree level throughout the 2019 in-leaf season. Because the research goal was to estimate benefits for only 2019, this method allowed for a targeted, one-year snapshot estimation rather than a cumulative multi-year assessment. We did not use data from 2023 or 2024 because the study only looked at the 2022 field measurements and the 2019 modelling timeframe.

2.7. Quantifying Dry Deposition of $PM_{2.5}$

Dry deposition for each street tree was calculated for each hour (t) by multiplying deposition velocity (V_d), the concentration of ambient air pollutants (C_t), deposition time (t), with total crown projection area as the surface area of deposition (A), using Equation (5) [33,55]:

$$d = V_d \cdot C_t \cdot t \cdot A \quad (3)$$

where

d = Amount of $PM_{2.5}$ deposited at time t (g);

V_d = Deposition velocity at time t (cm s^{-1});

C_t = $PM_{2.5}$ concentration at time t (μg m^{-3});

t = deposition duration (s);

A = deposited area (m^2).

The total amount of $PM_{2.5}$ removed by city-owned street trees is

$$D = \Sigma\, d \quad (4)$$

where

D = total amount of $PM_{2.5}$ deposited for all street trees across the city (g);

d = total amount of $PM_{2.5}$ deposited at the individual tree level (g).

3. Results

3.1. Descriptive Statistics

Our study investigated the dry deposition of $PM_{2.5}$ by 200,560 city-owned street trees across 245 unique tree species. The average DBH is 17.31 cm (95% CI: [17.22, 17.39]), and the median DBH is 26.65 cm. *Acer platanoides* is the most common species, representing 17.8% of trees, followed by *Gleditsia triacanthos* var. *inermis* (8.4%), *Picea pungens* (6.1%), *Malus* spp. (5.1%). *Syringa reticulata* 'Ivory Silk' (4.1%), *Acer platanoides* 'Schwedleri' (3.8%), *Acer saccharinum* (3.4%), *Gleditsia triacanthos* 'Skyline' (2.8%), and *Acer platanoides* 'Columnare' (2.6%). The following tree species are each represented by a single tree in the dataset: *Corylus americana*, *Fraxinus americana* 'Autumn Purple', *Fraxinus quadrangulate*, *Euonymus alatus*, *Taxus canadensis*, *Catalpa ovata*, *Syringa* × *chinensis*, *Crataegus laevigata*, *Prunus glandulosa*, *Abies fraseri*, *Spiraea* × *bumalda* 'Gold Flame', *Laburnum anagyroides*, *Prunus cerasifera* 'Newport', *Fraxinus pennsylvanica* 'Patmore', *Morus rubra*, *Cornus sericea*, *Ulmus glabra*, *Magnolia stellata*, *Liquidambar styraciflua*, *Fraxinus americana* 'Kleinburg', *Ulmus glabra.* We obtained daily wind data from local weather stations throughout the study period. During this time, the minimum recorded wind speed was 0 m/s, the maximum was 13.33 m/s, and the average wind speed was 5 m/s. By integrating wind speed data with the tree inventory, this study assessed its impact on deposition velocity across various city-owned tree species.

3.2. Dry Deposition of $PM_{2.5}$ by City-Owned Street Trees

City-owned Street trees captured 27.8 tons of $PM_{2.5}$ through dry deposition during the in-leaf season (1 May to 30 September) of 2019, as seen in Table 1. Coniferous trees, despite comprising only 14.37% of the total tree population, account for 92.15% of total $PM_{2.5}$ deposition; however, deciduous trees, representing 85.63% of all trees, contribute only 7.85% of $PM_{2.5}$ deposition. The list of $PM_{2.5}$ deposition by city-owned street trees is presented in Supplementary Materials Table S2.

Table 1. A comparison of coniferous and deciduous trees in total $PM_{2.5}$ deposition and their proportional representation in the tree population.

Tree Type	Total $PM_{2.5}$ Deposited (g)	Percentage of Total $PM_{2.5}$ Deposition (%)	Total Number of Trees	Percentage of Total Trees (%)
Coniferous	25,618,149.74	92.15	28,827	14.37
Deciduous	2,180,926.57	7.85	171,733	85.63
Total	27,799,076.31	100.00	200,560	100.00

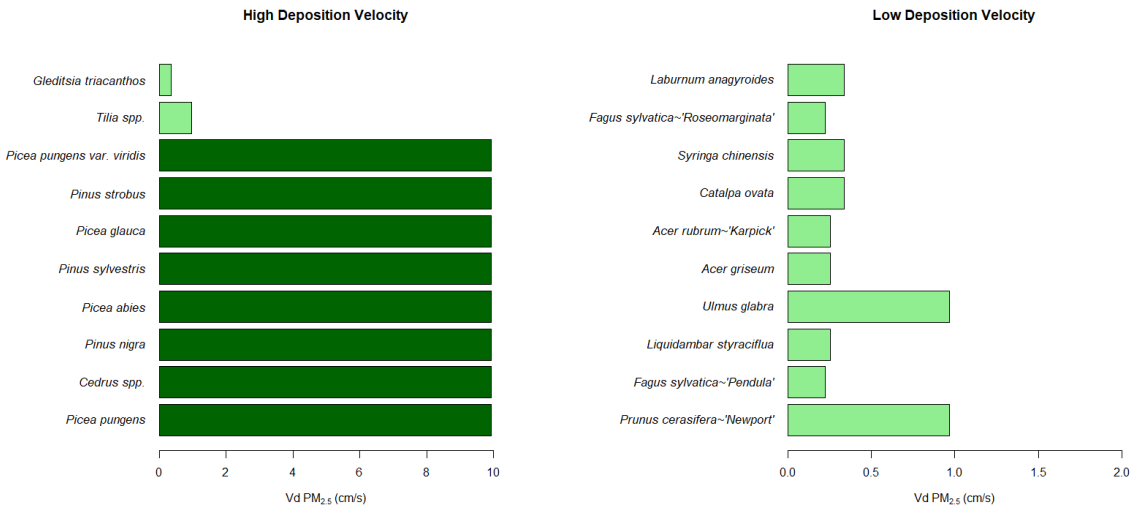
Picea pungens was the top-performing species in $PM_{2.5}$ reduction, intercepting 18.33 tons, accounting for 65.94% of the total dry deposition by all city-owned street trees during the study period (Table 1 and full list in Supplementary Materials Table S2). On average, each *Picea pungens* captured 1.79 kg of $PM_{2.5}$ during the in-leaf season of 2019. *Pinus nigra* follows with 5004 trees, removing 3.28 tons (11.82% of total $PM_{2.5}$ captured) through dry deposition, averaging 0.66 kg per tree. With 1535 trees, *Picea abies* captured 1.48 tons (5.39% of total $PM_{2.5}$ captured) at an average rate of 0.98 kg per tree. *Pinus sylvestris*, totaling 1378 trees, captured 0.60 tons (2.15% of total $PM_{2.5}$ captured) with an average of 0.43 kg per tree. *Picea glauca*, totaling 2322, collectively captured 0.54 tons of $PM_{2.5}$, representing 1.93% of the total amount of $PM_{2.5}$ captured. With 702 trees, *Pinus strobus* captured 0.50 tons (1.83% of the total), averaging 0.72 kg per tree. *Picea pungens*, with 2632 trees, captured 0.42 tons (1.51% of the total) with an average of 159.70 g per tree. *Tilia cordata*, totaling 12,324 trees, captured 0.34 tons (1.21% of the total) with an average of 27.36 g per tree. With 3285 trees, *Quercus rubra* captured 0.25 tons (0.89% of the total),

averaging 75.22 g per tree. *Acer platanoides*, the most numerous with 35,690 trees, captured 0.24 tons (0.85% of the total) with an average of 6.63 g per tree.

3.3. Species-Specific Deposition Rates

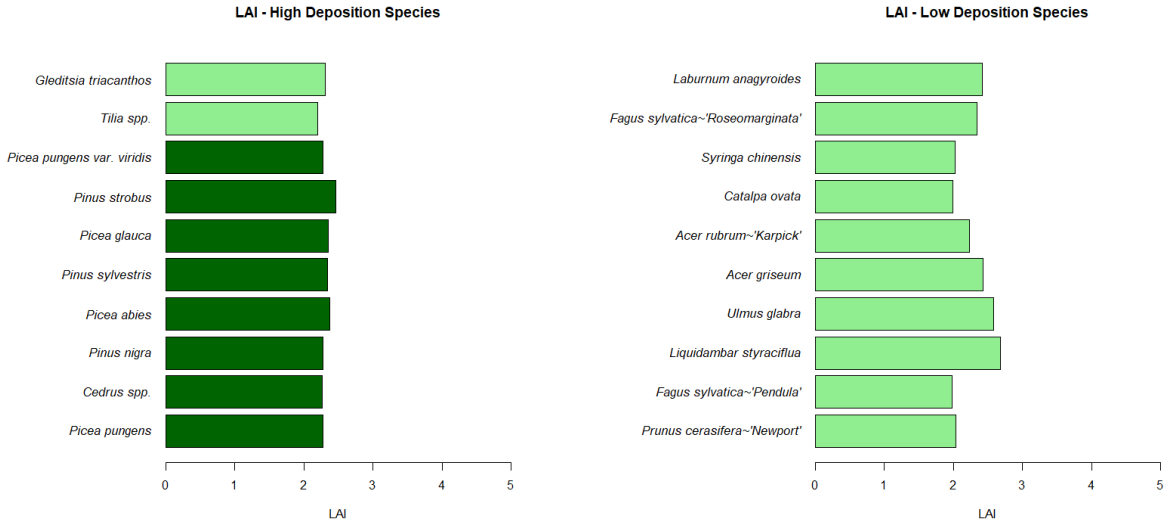
The top ten tree species noted for their $PM_{2.5}$ removal capabilities include *Picea pungens*, *Pinus nigra*, *Picea abies*, *Pinus sylvestris*, *Picea glauca*, *Pinus strobus*, *Picea pungens*, *Tilia cordata*, *Quercus rubra*, and *Acer platanoides* (Figure 5, Table 2 and Supplementary Materials Table S2 for the complete list of tree species). These ten species collectively account for 93.52% of the total $PM_{2.5}$ captured through dry deposition despite constituting only 37.46% of the city-owned street tree population. Among the top ten tree species that are most capable of mitigating $PM_{2.5}$ at the species level and individual tree level, *Picea pungens*, *Pinus nigra*, *Picea abies*, *Pinus sylvestris*, *Picea glauca*, *Pinus strobus*, *Picea pungens* are coniferous trees capable of removing 25.18 tons or 90.56% of the total $PM_{2.5}$ removal by all city-owned street trees. Alternatively, Tilia cordata, Quercus rubra and Acer platanoides are deciduous trees capable of removing 1.26 tons or 2.95% of the total $PM_{2.5}$ removal.

The top ten tree species identified for the $PM_{2.5}$ removal capabilities are characterized by high efficiency in $PM_{2.5}$ mitigation and exhibit a range of notable traits (Figure 5). Coniferous species such as *Picea pungens* (9.944 cm/s), *Pinus nigra* (9.944 cm/s), and *Picea abies* (9.944 cm/s) demonstrated the highest deposition rates among the ten species, indicating high effectiveness in capturing $PM_{2.5}$ from the atmosphere. LAI values are relatively high for the ten tree species that are most effective at removing $PM_{2.5}$, ranging from 2.197 to 2.465, which enhances the species' ability to intercept airborne pollutants. DBH measurements for tree species indicate robust growth, with *Picea pungens* leading with an average DBH of 32.29 cm, followed by *Pinus nigra* at 27.44 cm and *Picea abies* at 34.14 cm. The total area for $PM_{2.5}$ deposition per species in this group ranges greatly, with *Picea pungens* leading at 90.21 cm^2, reflecting the species' substantial contribution to air quality improvement in urban settings. The rest of the tree species showed an average deposited area per species ranging from approximately 10.43 cm^2 to 45.52 cm^2, highlighting their effective capability in capturing and retaining $PM_{2.5}$.

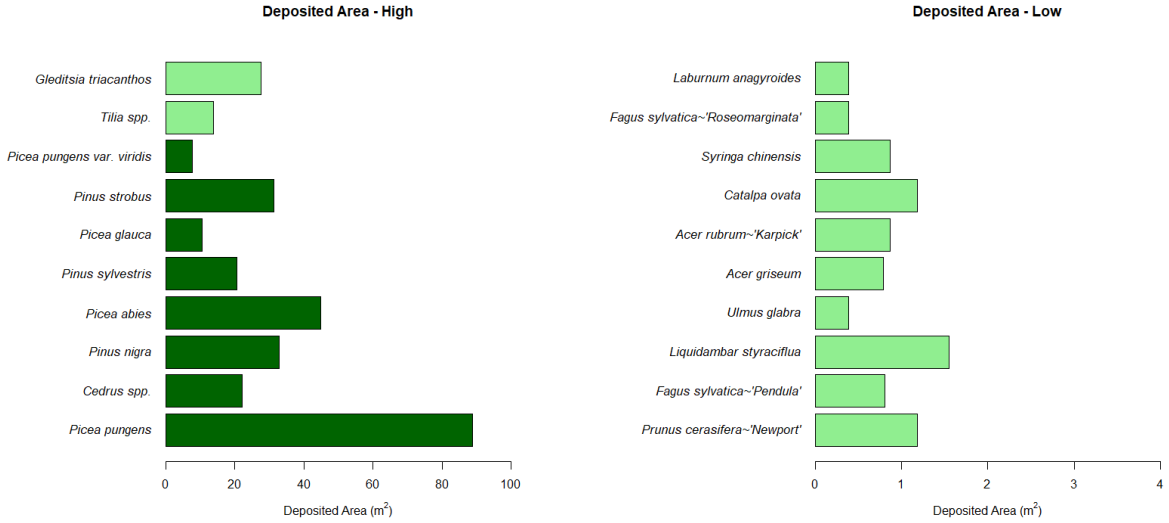


(**a**)

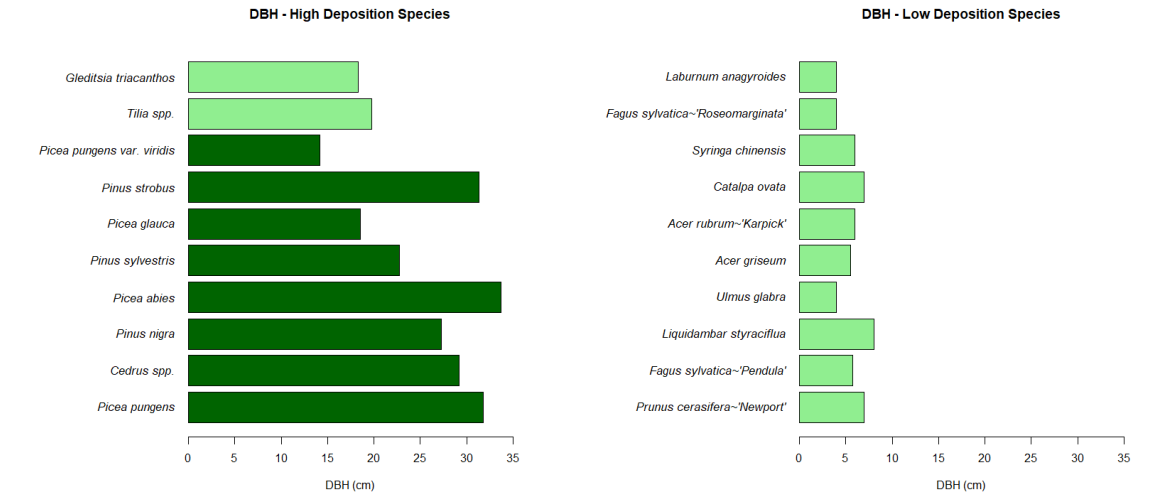
Figure 5. *Cont.*



(**b**)



(**c**)



(**d**)

Figure 5. A comparison of (**a**) average dry deposition velocity (cm/s), (**b**) LAI, (**c**) deposited area (m^2), and (**d**) DBH (cm) between high $PM_{2.5}$-mitigation species on the left and low-mitigation species on the right.

Table 2. $PM_{2.5}$ deposition at the species level for the top ten city-owned street trees during the in-leaf season of 2019 in Mississauga, Canada.

Scientific Name	Amount of $PM_{2.5}$ Deposited Per Species (g)	Percent of Total Deposition Per Species (%)	Number of Trees Per Species	Percent of Total Trees (%)	Amount of $PM_{2.5}$ Deposition Per Tree (g)
Picea pungens	18,329,696	65.94	10,248	5.11	1788
Pinus nigra	3,286,017	11.82	5004	2.5	656
Picea abies	1,498,729	5.39	1535	0.77	976
Pinus sylvestris	598,184	2.15	1389	0.69	430
Picea glauca	535,588	1.93	2322	1.16	230
Pinus strobus	507,412	1.83	702	0.35	722
Picea pungens	420,318	1.51	2632	1.31	159
Tilia	337,173	1.21	12,324	6.14	27
Quercus rubra	247,104	0.89	3285	1.64	75
Acer platanoides	236,688	0.85	35,690	17.8	6

The species with the lowest $PM_{2.5}$ reduction potential included *Cornus sericea*, *Viburnum trilobum*, *Liquidambar styraciflua*, *Magnolia stellata*, *Ulmus glabra*, *Acer griseum*, *Acer rubrum* 'Karpick', *Catalpa bungei*, *Syringa* × *chinensis*, and *Laburnum anagyroides*, which are the ten species that mitigate the least amount of $PM_{2.5}$ through dry deposition (Figure 5). Despite varying in number from one to three trees per species, each contributes only a small portion of the total deposition, totalling 10.13 g across all ten species. *Cornus sericea* has the highest deposition rate, averaging 1.55 g per tree, followed by *Viburnum trilobum* (1.36 g) and *Liquidambar styraciflua* (1.00 g). The next seven tree species that can mitigate $PM_{2.5}$ are *Magnolia stellata*, *Ulmus glabra*, *Acer griseum*, *Acer rubrum* 'Karpick', *Catalpa ovata*, *Syringa* × *chinensis*, and *Laburnum anagyroides*, all of which have a total $PM_{2.5}$ deposited of less than one gram per species.

Trees with lower $PM_{2.5}$ removal efficiency have lower $PM_{2.5}$ deposition velocities (Figure 5). The ten species have lower deposition velocities (V_d), averaging around 0.97 cm/s for *Cornus sericea*, 0.25 cm/s for *Liquidambar styraciflua*, and 0.25 cm/s for *Magnolia stellata*, indicating reduced capability in $PM_{2.5}$ capture compared to the first group, with the species most capable of removing $PM_{2.5}$ through dry deposition. Ten tree species that are least capable of removing $PM_{2.5}$ have LAI values ranging from 2.00 to 2.68, indicating comparatively less foliage density for pollutant interception. DBH measurements for the species are notably smaller, with averages such as approximately 0.39 cm for *Cornus sericea* and *Magnolia stellata* and 1.55 cm for *Liquidambar styraciflua*. The average total area for $PM_{2.5}$ deposition per species in this group ranges from approximately 1.98 cm^2 to 2.68 cm^2, limiting the impact on $PM_{2.5}$ reduction in urban environments.

4. Discussion

4.1. Advancing Approaches to Quantify $PM_{2.5}$ Deposition by City-Owned Street Trees

Our study reveals that Mississauga's 200,560 city-owned street trees (245 species) mitigate 27.8 tons of $PM_{2.5}$ during the in-leaf season (May–September 2019). This finding indicates how $PM_{2.5}$ removal varies greatly with urban tree composition and management scope compared to prior research. For example, Nowak et al. [43] estimated annual removals of 4.7–64.5 tons across entire urban forests (all tree types) in Syracuse and Atlanta, while Selmi et al. [44] reported 0.9 tons/km^2/year for Strasbourg's urban canopy. Critically, these studies did not isolate city-owned street trees—a key distinction, as our work demonstrates their outsized role in urban $PM_{2.5}$ mitigation due to targeted placement and management.

Further, while Janhäll [55] identified leaf microstructure as a driver of deposition, such traits are rarely incorporated into city-scale models. Unlike past studies that homogenized tree function, our species-level analysis highlights how conifers (e.g., *Picea pungens*) dominate $PM_{2.5}$ capture due to traits like high leaf-area index and deposition velocity. Focusing on street trees—a manageable municipal asset—we provide actionable insights for optimizing urban forests to improve air quality.

In contrast to previous models that assumed homogeneity in canopy structure and leaf area (e.g., [43,64], our species-specific approach reveals dramatic variability in $PM_{2.5}$ deposition rates, with the most efficient species (*Picea pungens*) capturing 77 times more $PM_{2.5}$ than the least efficient (e.g., *Acer platanoides*; see Table 1). This variability suggests the limitations of past studies: Escobedo and Nowak [65] reported $PM_{2.5}$ removal rates of 0.2–1.0 tons/year/ha in Santiago, Chile, using generalized canopy traits, while Tallis et al. [66] applied similar simplifications for London's urban forest. Such approaches mask critical differences; for example, our data show conifers (e.g., *Picea abies*; see Table 1) achieve 54 times higher deposition rates per tree than broadleaf species (e.g., Tilia; see Table 1) due to leaf-area density and surface roughness.

Critically, our model advances prior work in three ways: (1) individual-tree resolution (vs. city-scale estimates), (2) integration of species-specific traits (e.g., LAI and DBH) to reduce homogeneous canopy models (see Section 2). This precision enables targeted urban forestry—e.g., prioritizing high-LAI conifers in pollution hotspots—to maximize $PM_{2.5}$ removal.

4.2. Species-Specific Contribution to $PM_{2.5}$ Mitigation

Our findings align with and expand upon prior research on urban trees' role in $PM_{2.5}$ mitigation, highlighting key variations due to climate, urban structure, and species composition. Nowak et al. [43] estimated an average removal of 4.7–64.5 tons/year (0.13–0.32 tons/km^2/year) across ten U.S. cities, whereas our study found 27.8 tons during the in-leaf season (0.10 tons/km^2) in Mississauga. $PM_{2.5}$ deposition by city-owned street trees during the in-leaf season (1 May to 30 September 2019) exceeds the annual $PM_{2.5}$ mitigation by canopies in Syracuse, San Francisco, Philadelphia, Minneapolis, Boston, and Baltimore, US. This difference in $PM_{2.5}$ deposition between Toronto and U.S. studies listed above likely stems from Mississauga's suburban layout, where dense roadside tree plantings target high-emission zones, unlike the fragmented canopies in Nowak's study. Baro et al. [67] reported even lower removal (0.13 tons/km^2/year) in Barcelona, reinforcing the role of urban form, as compact cities with limited roadside vegetation may constrain $PM_{2.5}$ capture despite comparable canopy cover.

Species composition and growing season duration further explain disparities in deposition rates. Our data show that conifer-dominated areas in Mississauga achieved 0.28 tons/km^2/season, compared to 0.17 tons/km^2/season in deciduous species—a pattern consistent with Beckett et al. [20,21] who noted evergreens' superior PM removal but lacked landscape-scale quantification. Selmi et al. [44] reported 0.9 tons/km^2/year in Strasbourg, a deciduous-dominated city, where seasonal foliage loss reduces annual efficiency. This aligns with our finding that conifers sustain higher deposition, particularly in winter when deciduous trees are leafless. These comparisons suggest the need for species-specific planning to maximize $PM_{2.5}$ removal.

Earlier models often oversimplified species differences, leading to less precise estimates, using uniform leaf area metrics across Barcelona's urban forest, yielding a generalized 0.13 tons/km^2/year [67]. In contrast, our species-specific approach reveals stark variations: *Pinus strobus* mitigated 1.15 tons/km^2/year (seasonally adjusted), while *Acer saccharinum* mitigated only 0.46 tons/km^2/year—differences attributable to leaf area and

canopy structure. This refinement addresses limitations in past studies [43,64] that treated urban canopies as homogeneous, offering actionable insights for tree selection and air quality planning.

4.3. Refining the Theoretical Framework for Ecosystem Services by City-Owned Street Trees

Previous frameworks, such as those used in i-Tree Eco, have often treated trees as a homogeneous group, relying on generalized parameters to estimate $PM_{2.5}$ removal. For example, i-Tree Eco provided city-wide averages of $PM_{2.5}$ deposition without accounting for variability in species-specific traits, such as leaf area, surface roughness, or canopy structure. While useful for broad-scale assessments, this approach limits the development of targeted strategies for optimizing $PM_{2.5}$ removal through urban tree planting. Similarly, Nowak et al. [43] and Selmi et al. [44] used simplified frameworks that focused on aggregate urban forest function, overlooking the important role of species-specific differences in deposition processes.

In contrast, our study challenges these assumptions by emphasizing the importance of species-specific traits in dry deposition. We demonstrate that coniferous trees, particularly Picea pungens, are highly effective at capturing $PM_{2.5}$ due to traits such as high surface roughness, year-round dense canopies, and needle-like leaves. This finding aligns with Freer-Smith et al. [22], who found that conifers' waxy surfaces and fine structures enhance particulate capture in controlled environments. However, unlike Freer-Smith et al. [22], whose work was limited to laboratory settings, our study provides real-world, species-specific data from this extensive urban tree inventory, offering a more practical and scalable framework for urban forestry management.

Our framework also advances beyond previous models by incorporating local environmental factors, such as wind speed and pollution concentration, which considerably influence $PM_{2.5}$ deposition. This contrasts with earlier studies, such as Baró et al. [67] and Escobedo et al. [63], which assumed homogeneity in canopy structure and leaf area, leading to generalized estimates. For instance, Baró et al. [67] and Nowak et al. [43] reported $PM_{2.5}$ removal rates in Barcelona and U.S. cities using a simplified model that did not account for species-specific traits. While these studies provided valuable insights, their reliance on simplified parameters limited their accuracy and applicability to specific urban contexts. By integrating species-specific traits and environmental variables, our framework offers a more precise and actionable approach to quantifying $PM_{2.5}$ removal.

In addition to methodological advancements and species-specific insights, our study refines theoretical frameworks for understanding how urban trees mitigate air pollution. Rather than trees from parks or natural areas in the city [68,69], our study demonstrated that city-owned street trees are an integral component of urban green infrastructure that necessitates strategic planning and management [70,71]. Research aids cities in optimizing tree placement, species selection, and maintenance to maximize the cost-effectiveness and benefits of tree planting [72–74]. Street trees are often unevenly distributed across neighbourhoods, with higher-income groups typically residing in areas with greater urban canopy cover [75,76]. Research in this area highlights the need to promote equitable access to tree canopy and enhance the ecosystem services provided by street trees, such as mitigating urban heat islands, managing stormwater runoff, and enhancing biodiversity [77–79]. These efforts are crucial for maximizing human health and well-being, particularly in densely populated urban centres.

4.4. Practical Implications Through a Data-Driven Framework for Species Selection to Maximize $PM_{2.5}$ Removal

The study enhances our comprehension of street trees as natural solutions for improving urban air quality. This study's findings contribute to our analysis of $PM_{2.5}$ deposition at

the individual tree level and elucidate how species-specific traits influence $PM_{2.5}$ capture. *Picea pungens*, *Pinus nigra*, and *Picea abies* exhibit an estimated deposition velocity ($V_{d\ PM2.5}$) of around 9.944 cm/s, indicating these species' efficient $PM_{2.5}$ capture. *Picea pungens* and *Picea abies*, with substantial DBH values (32.29 cm and 34.14 cm, respectively), as seen in Figure 5, leading to substantial deposited areas per species, ranging from approximately 10.43 cm^2 to 90.21 cm^2, emphasizing that coniferous species with larger tree sizes can effectively capture and retain $PM_{2.5}$ [80]. The study provides empirical data for prioritizing coniferous species and planting locations in urban areas, ensuring that resources are allocated efficiently to maximize environmental benefits [26,35]. Future research could build on this framework to investigate additional environmental pollutants and explore their interactions with dynamic urban climatic variables. Such work would refine urban forestry strategies for air quality management and enhance their applicability in diverse urban contexts [81]. Urban planners and environmental managers in global cities can make informed decisions to enhance the ecological services provided by urban forests through air pollution mitigation, public health improvement and biodiversity.

4.5. Limitations and Suggestions for Future Work

This study has several limitations that must be acknowledged. Temporally, the study focuses on the in-leaf season, which may underestimate the annual contribution of coniferous trees to $PM_{2.5}$ removal. Coniferous trees retain their foliage and continue to capture $PM_{2.5}$ throughout the winter in Mississauga [20–22,24]. This seasonal focus may not fully capture the year-round benefits of urban forests, particularly in regions with considerable winter pollution. Spatially, the study relies on $PM_{2.5}$ concentration data at a 1 km resolution and Leaf Area Index (LAI) data at a 3 m resolution. This discrepancy in spatial resolution could impact the accuracy of $PM_{2.5}$ dry deposition estimates, particularly in areas with high spatial heterogeneity in pollution levels [82]. The coarser resolution data may not effectively capture fine-scale variations in $PM_{2.5}$ concentrations, which are influenced by localized sources such as traffic and industrial emissions.

Methodologically, the study uses DBH as a proxy for estimating the total surface area available for $PM_{2.5}$ deposition. While DBH provides a standardized metric for tree size, it fails to account for species-specific traits and tree characteristics such as branch length, density, and leaf area, which directly influence the total surface area available for deposition [35]. Additionally, the study employs a taxonomic order-based approach to generalize deposition velocities (V_d) for $PM_{2.5}$. Variabilities in dry deposition rates have been observed within the same plant order. For example, within the Pinales order [22,23], it was found that *Pseudotsuga menziesii* has a dry deposition rate of 2.1760 cm/s at a wind speed of 5 m/s, whereas *Pinus nigra* has a much higher rate of 9.9440 cm/s. *Quercus petraea* has a dry deposition rate of 1.5233 cm/s at a wind speed of 5 m/s, compared to only 0.2233 cm/s for *Alnus glutinosa*, which is estimated based on Beckett and Freer-Smith [23]. These examples demonstrate that species-specific traits such as leaf morphology, canopy structure, and stomatal conductance can greatly influence dry deposition rates, even among closely related species. This variability suggests the importance of considering species-level traits rather than broader taxonomic classifications.

For future research, we propose refining the temporal scope by using local precipitation data to identify and remove wet days, ensuring that the study period only includes dry deposition conditions. Future research should also expand the temporal scope to include year-round data to capture the full seasonal variation in $PM_{2.5}$ removal by urban trees. Longitudinal studies could assess how $PM_{2.5}$ deposition varies across seasons and climatic conditions. Additionally, higher-resolution spatial data for $PM_{2.5}$ concentrations and other relevant variables would improve the precision of dry deposition estimates, particularly

in areas with heterogeneous pollution levels. Future studies can expand to include trees in parks and woods near densely populated regions, where higher $PM_{2.5}$ concentrations and greater human exposure may occur. This can enhance the importance of urban trees in public health and equitable access to ecosystem services.

Incorporating species-specific traits, such as leaf morphology and canopy structure, into models could enhance the accuracy of deposition velocity estimates. Furthermore, integrating real-time environmental data, such as wind patterns and humidity, would provide a more comprehensive understanding of the factors influencing $PM_{2.5}$ deposition. Expanding the study scope to include all urban trees, not just city-owned street trees, would offer a more complete picture of the role of urban forests in air quality improvement. Although we aimed to refine dry deposition of $PM_{2.5}$ like i-Tree Eco, which often aggregates data at the city scale, future work should combine a species-specific approach with spatial analysis of built–environment factors in urban morphology, such as street canyons, density of tree planting or clustered planting [83–87] to optimize $PM_{2.5}$ mitigation.

5. Conclusions

We quantified $PM_{2.5}$ deposition by city-owned tree species in Mississauga, Canada, during the in-leaf season of 2019, highlighting the important role of urban street trees in mitigating air pollution. This study's key contribution is using individual tree-based $PM_{2.5}$ deposition estimates. Our findings reveal that city-owned street trees mitigated 27.8 tons of $PM_{2.5}$ via dry deposition, with coniferous species contributing disproportionately to this removal despite their lower representation in the tree population. In particular, coniferous trees, which comprise only 14.37% of the total tree population, accounted for 25.63 tons (85.63% of total deposition) of $PM_{2.5}$ deposition, compared to 2.18 tons by deciduous trees. Among the 245 studied species, *Picea pungens* accounted for the largest regional $PM_{2.5}$ removal, contributing 18.33 tons (65.94%) of the total deposition across the study area. *Pinus nigra* ranked second (3.29 tons, 11.82%), followed by *Picea abies* (1.50 tons, 5.39%), *Pinus sylvestris* (0.60 tons, 2.15%), and *Picea glauca* (0.54 tons, 1.93%). The dominance of these conifers reflects their abundance in the urban canopy, combined with high deposition velocity, large LAI and DBH, and broad crown areas—factors that collectively enhance $PM_{2.5}$ capture at the landscape scale.

These findings emphasized the critical role of coniferous trees in urban air quality improvement and suggested that urban forestry strategies should consider species-specific traits to optimize pollution mitigation. Future studies should explore year-round deposition rates, refine model assumptions, and evaluate the ecological and social implications of prioritizing high-deposition species in urban planning. By integrating these considerations, urban forestry can contribute more effectively to sustainable, healthier urban environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14101969/s1, Table S1: Dry deposition velocity (V_d, cm s^{-1}) of tree species [20,23] for (a) deciduous species and (b) coniferous species. Table S2: Dry deposition of $PM_{2.5}$ by city-owned street trees in Mississauga during 1 May to 30 September 2019. Table S3: Species matching for city-owned street trees.

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Abbreviations

The following abbreviation is used in this manuscript:

$PM_{2.5}$	fine particulate matter

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