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Ranking the suitability of common urban tree species for controlling $PM_{2.5}$ pollution

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ABSTRACT

Pollution caused by particles with aerodynamic diameters less than 2.5 µm ($PM_{2.5}$) is now a major environmental problem in many Asian cities. Planting more trees has been suggested as an unconventional approach to alleviate the problem. In this study, we developed a ranking approach to evaluate the $PM_{2.5}$ removal efficiency, negative impacts on air quality, and the suitability to urban environments of commonly occurring urban tree species. The results showed that the most frequently occurring tree species in global cities were not the best performers in removing $PM_{2.5}$. Among the ten most frequently occurring tree species, only London plane (*Platanus acerifolia* (Aiton) Wild.), silver maple (*Acer saccharinum* L.) and honey locust (*Gleditsia triacanthos* L.) were ranked above average. However, there is great potential for improving the removal of $PM_{2.5}$ from urban air by using species that have high $PM_{2.5}$ removal efficiency, especially conifer species. Use of conifer species requires choosing the correct gender and matching trees with appropriate sites. The results from this study can assist environmental management agencies in the selection of tree species for urban greening projects focusing on $PM_{2.5}$ control.

Keywords: *Air pollutant, urban environment, urban greening, biophysical characteristics*

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1. Introduction

High concentrations of $PM_{2.5}$ in urban air pose a great health risk to urban residents. Epidemiological studies have already shown the linkage between $PM_{2.5}$ pollution in cities and an increase in respiratory and cardiovascular diseases and premature deaths (Mate et al., 2010; Nawahda et al., 2012). Recently, $PM_{2.5}$ pollution has increased in Asian cities (Yu et al., 2011; Tiwari et al., 2012) making it the top public health concern in this region (Nawahda et al., 2012). Administrations in affected cities face mounting pressure from the general public to control $PM_{2.5}$ pollution.

Conventional measures for controlling $PM_{2.5}$ pollution focus on reducing emissions from sources (Tucker, 2000; Mölders, 2013; Pui et al., 2014). These measures cannot deal with the $PM_{2.5}$ already in the air. Urban trees, an unconventional solution to the problem, have been shown to remove $PM_{2.5}$ from the air (Nowak et al., 2013). Urban trees reduce $PM_{2.5}$ pollution both directly and indirectly. In direct reduction, tree canopies intercept $PM_{2.5}$ with their branches and leaves (Beckett et al., 1998; Freer–Smith et al., 2004; Saebo et al., 2013). In a study of ten U.S. cities, Nowak et al. (2013) found that the amount of $PM_{2.5}$ removed directly from urban air by trees varied between 4.7 t/year and 64.5 t/year in different cities. Indirectly, trees lower air temperatures through shading and evapotranspiration. The cooling effect reduces the need for energy–using fans and air conditioners, which further lowers emissions from power plants. Also, the rates of photochemical reactions in the urban atmosphere are slowed by the lowered air temperature resulting in decreased production of secondary air pollutants (Nowak et al., 2000).

The direct removal of $PM_{2.5}$ by trees is affected by environmental factors as well as the biophysical characteristics of trees (Zhao et al., 2013). Environmental factors such as weather conditions, urban morphology, and concentrations of $PM_{2.5}$ have a significant impact on the quantity of $PM_{2.5}$ intercepted by trees (Beckett et al., 2000a; Reinap et al., 2009). Biophysical characteristics at the group level such as planting density, spatial arrangement, total leaf surface area, and phenology are the main influencing factors (Hagler et al., 2012; Nowak et al., 2013; Brantley et al., 2014). At the individual tree level, tree dimension, canopy texture, leaf characteristics, and growth habits define a species' $PM_{2.5}$ removal efficiency (Abdollahi, 2000; Fuller et al., 2009; Huang et al., 2013). Studies have shown that trees with larger leaf surface areas have higher $PM_{2.5}$ removal efficiency (Lorenz and Murphy, 1989). Evergreen conifers have higher efficiency because they maintain high leaf surface areas all year round. Trees with dense canopies and fine textures have higher surface roughness that can facilitate the interception of $PM_{2.5}$ (Freer–Smith et al., 2004; Freer–Smith et al., 2005; Petroff et al., 2008). At the leaf level, leaves with complicated structures and rough, sticky, or waxy surfaces can capture and retain $PM_{2.5}$ more efficiently (Wedding et al., 1975; Little and Wiffen, 1977; Abdollahi, 2000; Saebo et al., 2012).

Because $PM_{2.5}$ removal efficiency varies among tree species, it is advisable to use species with high $PM_{2.5}$ removal efficiency in urban greening projects. However, high $PM_{2.5}$ removal efficiency is not the only criterion for species selection. An important consideration is the species' ability to adapt to urban environments. Trees growing in urban environments are subjected to various abiotic and biotic stresses such as compacted soil, waterlogging, droughts, pests and diseases, and air pollutants (Pauleit, 2003; Nielsen et al., 2007; Jutras et al., 2010). If trees cannot tolerate these conditions, growth can be stunted and life span reduced. A tree with a poorly developed canopy will be less effective in intercepting $PM_{2.5}$. Tree species susceptible to pests and disease have to be treated with pesticides which are another source of $PM_{2.5}$ (Coscolla et al., 2008). The removal and replacement of dead trees contributes to increased $PM_{2.5}$ emissions if automobile transportation and power tools are used (Escobedo et al., 2011).

Tree species that impair air quality should be avoided or planted less frequently. People can be allergic to the pollen from some tree species (Hruska, 2003). Biogenic volatile organic compounds (BVOCs) emitted by trees can react with nitrous oxides (NO_X) and other chemical species to form ozone (O_3) and secondary organic aerosols (SOAs). O_3 is the main component of urban smog. SOA is a source of $PM_{2.5}$ (Benjamin and Winer, 1998; Setyan et al., 2012). Emission rates of BVOC vary greatly among tree species. Species with low emission rates are preferred in urban greening projects (Nowak et al., 2000).

Although a few studies included the improvement of air quality as a criterion in selecting urban tree species (Nowak and Heisler, 2010; Tong et al., 2010), none of the studies has systematically evaluated the suitability of common urban tree species for greening projects targeting $PM_{2.5}$ pollution. Moreover, past studies focused mostly on particular regions so the results have limited use for cities in other regions. In this study we developed a ranking method and used it to evaluate the suitability of common urban tree species for controlling $PM_{2.5}$. Specifically, the objectives of this study include: (1) to find out what tree species commonly occur in global cities, and (2) to rank the suitability of those tree species for controlling $PM_{2.5}$. The method developed in this study and the evaluation results can assist environmental management agencies worldwide in selecting suitable tree species if they want to use urban greening as a $PM_{2.5}$ control tool.

2. Methods

2.1. Compiling a list of urban trees that are most commonly occurring within cities globally

An extensive literature search was conducted to compile a list of urban tree species commonly occurring around the world. Combinations of keywords including “urban”, “city”, “tree species”, “woody plants”, and “flora” were used in searching three online literature databases, including Scopus, ISI Web of Knowledge, and Google Scholar. Returned search results were filtered using the following two criteria: (1) the work was carried out within an urban area. In this study a place was deemed urban if it had a minimum of 2 500 inhabitants, and (2) the work focused on trees found in man–made landscapes such as streets, parks, and residential areas. Studies that were primarily conducted in natural reserves inside urban areas, remnant urban forests, and other types of natural forests were excluded in the analysis. Lists of tree species were extracted from studies that met the two criteria. If a paper did not contain a list of species which was mentioned in it, an e–mail was sent to the author requesting the information. A Google search was also conducted for urban tree inventory reports. Only inventory reports containing lists of tree species were downloaded and included.

Scientific names of identified species were verified against the Plant List database, the largest online database containing accepted scientific names for plant species (The Plant List, 2013). Species that did not have accepted scientific names were further verified using integrated taxonomic information system (ITIS, 2014). Species that could not be verified were discarded. Records at taxonomic levels lower than species (e.g. varieties and cultivars) were merged to the species level. After preprocessing, we counted the number of times that a particular species occurred in all studied cities to determine the relative frequency of this species among cities.

2.2. Ranking the suitability of tree species

Following the approach used in i–Tree Species Selector (Nowak, 2008), the relative efficiency of $PM_{2.5}$ of tree species was ranked using seven biophysical variables of trees (Table 1).

Biophysical variables of tree species were mainly collected from *Silvics of North America* (Burns and Honkala, 1990), Gilman and Watson (1993), and Horticopia (Horticopia, 2013). Ratings of variables were aggregated using a simple additive method.

The negative impacts on air quality were evaluated using criteria listed in Table 2.

Pollen allergenic ranks were obtained from Allergy–Free Gardening (2014), IMS Health (2014), and other literature (Lorenzoni–Chiesura et al., 2000; Hruska, 2003; Carinanos and Casares–Porcel, 2011). Standard BVOC emission rates of 51 species were obtained from Benjamin and Winer (1998). Measured emission rates per unit of dry biomass weight for the remaining 49 species were obtained from the Biosphere–Atmosphere interactions research group (BAI, 2013) and other references (Guenther et al., 1994; Kesselmeier and Staudt, 1999; Zhang et al., 2000). Following the procedure developed by Benjamin and Winer (1998), these measured emission rates were converted to standard emission rates by using algorithms developed by Guenther et al. (1993).

Five characteristics were used to evaluate a tree species’ adaptation to urban environments (Table 3).

Table 1. *Method for ranking $PM_{2.5}$ removal efficiencies of tree species*

Variables	Ratings and Criteria		
	3	2	1
Type	Evergreen conifer	Evergreen broadleaf	Deciduous
Size	Height of mature tree more than 20 m	Height of mature tree between 10 m and 20 m	Height of mature tree between 5 m and 10 m
Growth rate	Fast	Medium	Slow
Canopy structure	Dense canopy, fine texture	Canopy with medium density, medium texture	Open canopy, coarse texture
Leaf complexity	Bi– or tri–pinnately compound, or scale–like leaves in conifer	Pinnately or palmately compound; deeply–divided or lobed	Intact single leaf
Leaf size	Average size of leaf less than or equal to 5 cm	Average size of leaf between 5 cm and 20 cm	Average size of leaf more than 20 cm
Leaf surface feature	Rough, hairy, resinous, sticky, scaly, scurfy, glutinous, tufts	Ciliate, velvety, pubescent, waxy, glaucous, downy, slightly hairy, fuzzy	Smooth surface

Table 2. *Method for ranking the negative impacts on air quality by tree species*

Variables	Ratings and Criteria		
	3	2	1
Allergenic level of pollen	Highly allergenic	Medium	Low
BVOC emission rate	Emission rate of isoprene and monoterpenes more than 10 g day^{-1} $tree^{-1}$	Emission rate of isoprene and monoterpenes between 1 g day^{-1} $tree^{-1}$ and 10 g day^{-1} $tree^{-1}$	Emission rate of isoprene and monoterpenes less than or equal to 1 g day^{-1} $tree^{-1}$

Table 3. *Method for ranking the suitability for urban environments for tree species*

Variables	Ratings and Criteria		
	3	2	1
Tolerance of poor soil	Strong	Medium	Low tolerance, need good soil
Tolerance of drought	Strong	Medium	Low tolerance, need watering
Resistance to pest and disease	Strong	Medium	Susceptible to multiple pests and diseases
Tolerance of SO_2	Strong	Medium	Low to sensitive
Tolerance of O_3	Strong	Medium	Low to sensitive
Tolerance of NO_2	Strong	Medium	Low to sensitive

Tolerances of unfavorable soil conditions, droughts, pests and diseases of each species were obtained from NRCS (2014), Horticopia (2013), Hortipedia (2013), and UFEI (2012). Tolerances of SO_2, O_3 and NO_2 were obtained from various published papers and reports (U.S. EPA, 1976; Umbach and Davis, 1984; Kozlowski and Constantinidou, 1986a; Kozlowski and Constantinidou, 1986b; Li and Hu, 2005; Appleton et al., 2009). If information for a characteristic of a particular species was not available, it was left blank. Values of negative impacts on air quality and suitability to urban environments of tree species were not calculated due to missing data.

To save space, only important references were presented in the main text of this article. A complete list of references that were used to extract the aforementioned characteristics of trees was included in the Supporting Material (SM).

3. Results

3.1. Common urban tree species

A total of 3 602 tree species were identified in 328 cities in 60 countries (for names of cities and countries, see the SM, Table S1). These species belonged to 191 families and 1 115 genera. The ten most frequently occurring families, genera, and species in global cities were listed in Table 4.

3.2. Ranks of species

Based on occurrences of all species in studied cities, a list of the 100 most frequently occurring tree species was compiled (Table 5). Their $PM_{2.5}$ removal efficiency, negative impact on air quality, and suitability for urban environments were ranked. The table was ordered by the relative $PM_{2.5}$ removal efficiency of each species and then by the occurrence of the species.

4. Discussion

The list of species compiled in this study depicted a well–known trend showing that cities exhibit common genera and species. While there were no similar lists with which we could compare our list, our list could be compared to results from several regional studies. *Acer sp.* and *Tilia sp.* were among the top 10 most frequently occurring genera found in our list. They were also the top two genera found in 10 Nordic cities (Sjoman et al., 2012). Species such as Norway maple *(A. platanoides)* were most common in cities in the United Kingdom, the United States of America, and Australia (Kendal et al., 2012; Nowak, 2012), they were among the top ten on our list. These observations supported to the conclusion that "urban–adaptable" species are becoming increasingly widespread across the planet (McKinney, 2006).

Among the ten most frequently occurring species, the $PM_{2.5}$ removal efficiency of London plane (*P. acerifolia*), silver maple (*A. saccharinum*) and honey locust (*G. triacanthos*) were ranked as above average. Silver maple also has a low to medium negative impact on air quality and adapts to urban environments very well. The two most widely occurring species black locust (*R. pseudoacacia*) and Norway maple, have below average efficiency in $PM_{2.5}$ removal but they adapt well to urban environments and are often invasive. The remaining six species had properties similar to black locust and Norway maple. This result reflected the fact, in the past, urban tree species were mainly selected for their aesthetic values and adaptability to urban environments (Saebo et al., 2003). Expanding the selection criteria to include assessments of ecosystem services (e.g., air pollution reduction) generated by trees will allow us to make better decisions.

Conifer species were ranked high in $PM_{2.5}$ removal efficiency. This result was in agreement with field observations (Beckett et al., 2000b; Saebo et al., 2012). The higher effectiveness of conifers is due to the following factors: year round foliage, dense and fine–textured canopies, and high leaf area index. None of the conifer species, however, was among the top ten most frequently occurring species. In fact none of them was among the top twenty. This creates a unique opportunity to enhance the removal of $PM_{2.5}$ of urban forests by increasing the use of conifer species worldwide. A call for increased use of conifer species in urban greening programs to help control air pollution has been made by other researchers (Beckett et al., 2000b; Nowak and Heisler, 2010). Our results showed that conifer species are underused globally. Nevertheless, our results also indicated that caution needs to be taken when planting more conifers. For example eastern red cedar (*J. virginiana*) was ranked as a top species in $PM_{2.5}$ removal efficiency but its pollen is also highly allergenic. Therefore, male trees of eastern red cedar should be avoided in planting programs in cities. Eastern white pine (*P. strobus*) was ranked high in $PM_{2.5}$ removal efficiency but its tolerance of air pollutants was low. This limitation restricts its use in places with high levels of air pollution. Besides these concerns, the dense shade cast by conifers and their sensitivities to high salt levels in soils (Goodrich and Jacobi, 2012) are other factors that need to be considered.

There are broadleaf species which have high $PM_{2.5}$ removal efficiency, low negative impact on air quality, and good suitability for urban environments. Red maple (*A. rubrum*), silver linden (*T. tomentosa*), and American elm (*U. americana*) are a few examples. These findings showed that it was possible to construct an urban forest with both good species diversity and a high $PM_{2.5}$ removal efficiency.

Table 4. *Top ten most frequently occurring families, genera, and species of trees in 328 cities*

Rank	Family	Occurrences	Genus	Occurrences	Species	Occurrences
1	Leguminosae	260	*Acer sp.*	213	*Robinia pseudoacacia* L.	125
2	Rosaceae	241	*Fraxinus sp.*	179	*Acer platanoides* L.	124
3	Oleaceae	229	*Pinus sp.*	176	*Platanus acerifolia* (Aiton) Willd.	96
4	Aceraceae	213	*Prunus sp.*	170	*Gleditsia triacanthos* L.	95
5	Salicaceae	198	*Populus sp.*	168	*Acer saccharinum* L.	93
6	Pinaceae	195	*Quercus sp.*	164	*Acer negundo* L.	92
7	Malvaceae	191	*Ulmus sp.*	147	*Ailanthus altissima* (Mill.) Swingle	89
8	Ulmaceae	186	*Tilia sp.*	143	*Tilia cordata* Mill.	89
9	Fagaceae	184	*Platanus sp.*	142	*Betula pendula* Roth	84
10	Betulaceae	174	*Betula sp.*	127	*Morus alba* L.	83

The $PM_{2.5}$ removal efficiency estimated by this study measures the relative capacity of a tree species in removing $PM_{2.5}$ when it reaches mature size. Although the most reliable way to rank $PM_{2.5}$ removal efficiency among tree species is to directly measure the quantity of intercepted $PM_{2.5}$ using mature trees in a controlled environment, the feasibility of conducting that kind of study is low (Zhao et al., 2013). Current field measurements on $PM_{2.5}$ removal by trees were mainly conducted on tree seedlings, model trees, branches, or leaves (Abdollahi, 2000; Beckett et al., 2000b; Ould–Dada, 2002; Huang et al., 2013; Saebo et al., 2013). When scaling up those measurements to derive removal efficiencies of mature trees, unknown amount of uncertainties were introduced into the final estimates. Modeling studies mainly focused on groups of trees or urban forests (Nowak et al., 2013). They did not provide information on the $PM_{2.5}$ removal efficiency of individual tree species. Despite these limitations, the ranking approach used in this study and others (Nowak, 2008) provides a feasible way for people to assess the $PM_{2.5}$ removal efficiency of any tree species.

In this study, characteristics that affected a species' negative impacts on air quality and its suitability for urban environments were assigned ordinal values ranging from one to three. This is due to the fact that those characteristics were normally assessed in a qualitative way in the literature. For example, most studies classified trees' tolerances of O_3, NO_2, and SO_2 pollution as tolerant, intermediate tolerant, and sensitive (U.S. EPA, 1976; Kozlowski and Constantinidou, 1986a; Kozlowski and Constantinidou, 1986b). This qualitative classification has its merit. Even for trees belonging to the same species, noticeable variations can be observed in those characteristics because of the influence of genetic factors, growth, environmental conditions, and measuring methods. Broad classification can accommodate these variations better than using specific numeric values.

While the result of this study can provide useful information for environmental management agencies worldwide, one should pay attention to the following limitations when using the results. First, the common tree species discussed in this article refer to species frequently occurring in global cities, not necessarily species that have large numbers of individuals. This is because the list of species was compiled from various sources. Different sampling approaches used in these sources resulted in varied detectability of tree species and estimates of parameters of tree populations. Furthermore, only a small number of sources presented estimates of quantities of trees. Those limitations prevented us from identifying the most common species by using quantities of trees. The compiled list was dominated by tree species in cities from the U.S., China, Germany, Brazil, Canada, and Slovakia where studies of urban vegetation have been conducted more extensively. Secondly, lack of information on BVOC emission rates, allergenicity of pollen, and air pollutants tolerance of some tree species limited our ability to perform a comprehensive evaluation. More studies are urgently needed in the future to fill in the information gap. Meanwhile users can refer to local databases and available information on species from the same genus to make an informed guess. Third, in order to reach the necessary level of generalization in the results, some location–specific features of trees were not included in the ranking method, (e.g., adaptation of the species to the local climate). For the same reason, the ranking method did not consider the suitability of a species for a particular planting site. For example, for streets or other populated places, species like silver maple might need to be avoided because of the brittle wood (Roth, 2001) even though it has a relatively high rate of $PM_{2.5}$ removal efficiency. The users should modify the ranking system to meet their specific needs. Finally, the ranking method itself has limitations. Ranking results are decided by users' choices of variables and judgments of relative importance of different variables (Paruolo et al., 2013). A species' rank can vary if a different set of variables and weights are applied. Therefore, the ranking result from this study should be viewed as a general guideline for selecting species rather than absolute ranks.

5. Conclusions

Tree planting has been proposed as an unconventional measure to control $PM_{2.5}$ pollution. Knowing which tree species to plant is the first step to implement this approach. In this study an easy–to–use ranking method was developed to rank the relative suitability of common urban tree species for planting programs which include the removal of $PM_{2.5}$ as a target. The results showed that some widely–distributed urban tree species were not the best performers in removing $PM_{2.5}$. However, planners can enhance the reduction of $PM_{2.5}$ by using a mixture of conifer and broadleaf species that have high $PM_{2.5}$ removal efficiencies, good adaptability to urban environments, and fewer negative impacts on air quality. The application of the ranking method in a particular city can be enhanced by supplementing information such as adaptation to local climates, management costs, and features of planting sites. In future studies, the ranking method can be improved by incorporating more quantitative descriptions of tree species characteristics. Weights for various characteristics can be added to the ranking system when we have gained better knowledge of the relative importance of those characteristics on $PM_{2.5}$ removal efficiency.

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Table 5. *$PM_{2.5}$ removal efficiencies, negative impacts on air quality, and suitability for urban environment of the top 100 frequently occurring tree species*

Occurrence	Scientific Name	$PM_{2.5}$ Removal Efficiency							Sum	Negative Impact		Suitability for Urban Environment					
		Type	Growth Rate	Height	Crown Density and Texture	Leaf Complexity	Leaf Length	Leaf Characteristic		BVOC Emissions	Pollen Allergy	Soil Tolerance	Drought Tolerance	Pest. and Disease Resistance	SO_2 Tolerance	O_3 Tolerance	NO_2 Tolerance
35	*Juniperus virginiana* L.	3	3	2	2	3	3	3	19	1	3	3	3	2	3	3	3
33	*Cupressus sempervirens* L.	3	2	2	3	3	3	3	19	1	1	3	3	1	3	3	2
45	*Juniperus chinensis* L.	3	2	2	2	3	3	3	18	1	3	3	3	2	3	3	3
69	*Thuja occidentalis* L.	3	1	2	3	3	1	3	16		2	3	2	1	3	3	2
43	*Pinus strobus* L.	3	3	3	2	1	2	2	16	2	1	2	2	1	1	2	1
38	*Taxodium distichum* (L.) Rich.	1	3	3	3	1	3	2	16	2	1	2	3	2	2	3	
31	*Tsuga canadensis* (L.) Carr.	3	1	3	2	1	3	3	16	1	1	2	2	1	2	3	
29	*Grevillea robusta* A.Cunn. ex R.Br.	3	3	3	2	2	1	2	16	1	2	2	3	2	2	2	
79	*Fraxinus excelsior* L.	1	3	3	2	2	2	2	15	1	3	3	3	1	2	3	
66	*Acer rubrum* L.	1	3	3	2	2	2	2	15	1	1	2	2	2	2	3	
66	*Populus alba* L.	1	3	3	1	2	2	3	15	2	2	3	3	1	3	1	3
53	*Picea abies* (L.) H.Karst.	3	1	3	2	1	3	2	15	2	1	2	2	1	2	3	2
51	*Ulmus pumila* L.	1	3	3	2	1	3	2	15	1	2	3	3	1	2	3	
50	*Picea pungens* Engelm.	3	1	2	3	1	3	2	15	2	1	3	2	1	3	3	2
45	*Tilia tomentosa* Moench.	1	3	3	2	1	2	3	15	1		3	2	2	2	3	1
43	*Ulmus americana* L.	1	3	3	2	1	2	3	15		2	2	3	1	2	3	2
38	*Salix alba* L.	1	3	3	3	1	2	2	15	2	3	3	3	2	1	2	
35	*Jacaranda mimosifolia* D. Don	1	3	2	2	3	3	1	15	1	2	2	3	2	1	3	
33	*Metasequoia glyptostroboides Hu and W.C.Cheng*	1	3	3	2	1	3	2	15	1	2	2	2	2	2	3	1
32	*Tilia ×europaea L.*	1	2	3	3	1	2	3	15		2	3	2	2	3		1
31	*Ulmus glabra Huds.*	1	3	3	2	1	2	3	15		2	3	2	2	2	2	3
96	*Platanus acerifolia (Aiton) Willd.*	1	3	3	2	2	1	2	14	2		3	3	1	3	2	2
95	*Gleditsia triacanthos L.*	1	3	3	2	3	1	1	14	1	1	3	3	1	2	1	

Table 5. *Continued.*

Occurrence	Scientific Name	$PM_{2.5}$ Removal Efficiency							Sum	Negative Impact		Suitability for Urban Environment					
		Type	Growth Rate	Height	Crown Density and Texture	Leaf Complexity	Leaf Length	Leaf Characteristic		BVOC Emissions	Pollen Allergy	Soil Tolerance	Drought Tolerance	Pest. and disease Resistance	SO_2 Tolerance	O_3 Tolerance	NO_2 Tolerance
93	*Acer saccharinum* L.	1	3	3	2	2	2	1	14	1	2	3	3	1	3	3	
73	*Acer pseudoplatanus* L.	1	3	3	2	2	2	1	14	1	2	3	2	1	2	3	
69	*Fraxinus pennsylvanica* Marshall	1	3	3	2	2	1	2	14	1		3	3	1	1	1	1
64	*Liriodendron tulipifera* L.	1	2	3	2	2	2	2	14	1	1	2	2	2	3	1	
59	*Pinus sylvestris* L.	3	2	2	2	1	2	2	14	2	1	3	3	1	1	2	1
58	*Salix babylonica* L.	1	3	3	3	1	2	1	14	3	3	3	3	2	1	2	3
56	*Acer saccharum* Marshall	1	2	3	2	2	2	2	14	1	2	2	2	2	3	3	
54	*Magnolia grandiflora* L.	2	2	3	2	1	2	2	14	1	1	3	2	2	3	3	
50	*Quercus palustris* Muenchh.	1	2	3	2	2	2	2	14		3	2	2	2	3	2	3
48	*Delonix regia* (Hook.) Raf.	2	3	2	2	3	1	1	14	1		3	3	3	1	2	
46	*Celtis occidentalis* L.	1	3	2	2	1	2	3	14	1	2	3	3	1	3	3	
46	*Pinus nigra* J. F. Arnold	3	2	2	2	1	2	2	14	2	2	2	3	1	2	1	1
40	*Sorbus intermedia (Ehrh.) Pers.*	1	3	2	2	1	2	3	14			2	2	1	3	3	
39	*Prunus serotina Ehrh.*	1	3	3	2	1	2	2	14	1	1	3	3	2	1	2	1
38	*Ficus benjamina L.*	2	3	2	3	1	2	1	14	2	2	2	2	2	1	1	
37	*Cedrus deodara (Roxb. ex Lamb.) G.Don*	3	3	2	2	1	1	2	14	1	1	3	3	3	1	2	
36	*Tilia americana L.*	1	2	3	2	1	2	3	14	1	2	3	2	2	2	2	1
35	*Zelkova serrata (Thunb.) Makino*	1	2	3	2	1	3	2	14	1	3	2	3	2	2	2	2
32	*Platanus occidentalis L.*	1	2	1	3	2	3	2	14	2	2	2	3	2	3	1	
32	*Populus tremula L.*	1	3	3	2	1	3	1	14	2	2	3	2	1	3		
30	*Ficus microcarpa L.f.*	2	3	2	3	1	2	1	14	2	2	2	2	1	3	3	
28	*Cinnamomum camphora (L.) J.Presl*	2	3	2	2	1	2	2	14	1	1	3	3	2	3	2	1
125	*Robinia pseudoacacia L.*	1	3	3	2	2	1	1	13	1	1	3	3	1	3	3	3
124	*Acer platanoides L.*	1	3	2	2	2	2	1	13	1	2	3	2	2	3	3	2

Table 5. *Continued.*

Occurrence	Scientific Name	PM$_{2.5}$ Removal Efficiency							Sum	Negative Impact		Suitability for Urban Environment					
		Type	Growth Rate	Height	Crown Density and Texture	Leaf Complexity	Leaf Length	Leaf Characteristic		BVOC Emissions	Pollen Allergy	Soil Tolerance	Drought Tolerance	Pest. and Disease Resistance	SO_2 Tolerance	O_3 Tolerance	NO_2 Tolerance
92	*Acer negundo L.*	1	3	2	2	2	2	1	13	1	3	3	3	1	2	2	2
89	*Tilia cordata Mill.*	1	2	3	2	1	2	2	13	1	2	3	2	2	3	3	1
83	*Morus alba L.*	1	3	1	2	2	2	2	13	1	3	3	3	2	1	1	
82	*Ginkgo biloba L.*	1	1	3	2	2	2	2	13	1	1	3	3	3	3	3	3
82	*Quercus rubra L.*	1	3	3	2	2	1	1	13	1	3	3	3	2	3	3	3
80	*Aesculus hippocastanum L.*	1	2	3	2	2	1	2	13	1	1	3	2	1	3	3	
70	*Fagus sylvatica L.*	1	2	3	2	1	2	2	13	2	1	2	2	2	3	3	3
69	*Juglans regia L.*	1	2	2	2	2	1	3	13	1	3	3	3	1	1	1	
63	*Populus nigra L.*	1	3	2	2	1	2	2	13	2	2	3	3	1	2	1	1
62	*Sorbus aucuparia L.*	1	2	1	2	2	3	2	13	1	1	1	2	1	2	2	1
61	*Acer campestre L.*	1	1	2	3	2	2	2	13	1		3	3	2	2	3	
54	*Crataegus monogyna Jacq.*	1	2	3	2	2	2	1	13	2	1	3	2	1	1	1	
53	*Fraxinus americana L.*	1	3	3	2	2	1	1	13		3	3	2	1	2	1	3
49	*Liquidambar styraciflua L.*	1	2	3	2	2	2	1	13	2	1	2	2	2	2	2	3
48	*Melia azedarach L.*	1	3	2	2	3	1	1	13	1	3	3	3	2	2	1	
43	*Populus deltoides W. Bartram ex Marshall*	1	3	3	1	1	2	2	13	2	2	3	3	1	2	1	
35	*Tilia platyphylla C.A.Mey.*	1	2	3	2	1	2	2	13		2	3	2	2	3	1	
30	*Quercus alba L.*	1	1	3	2	2	2	2	13	1	3	2	2	2	2	1	2
29	*Ficus carica L.*	1	2	2	2	2	1	3	13	2	2	2	2	1	3	3	
28	*Ficus elastica Roxb. ex Hornem.*	2	3	2	2	1	2	1	13	2	2	2	3	2	3		
89	*Ailanthus altissima (Mill.) Swingle*	1	3	3	1	2	1	1	12	1	1	3	3	2	3	2	
84	*Betula pendula Roth*	1	2	2	2	1	2	2	12	2	2	3	2	1	1	3	1
66	*Quercus robur L.*	1	2	2	2	2	2	1	12	2	3	2	3	1	3	3	3

Table 5. *Continued.*

Occurrence	Scientific Name	PM$_{2.5}$ Removal Efficiency							Sum	Negative Impact		Suitability for Urban Environment					
		Type	Growth Rate	Height	Crown Density and Texture	Leaf Complexity	Leaf Length	Leaf Characteristic		BVOC Emissions	Pollen Allergy	Soil Tolerance	Drought Tolerance	Pest. and Disease Resistance	SO_2 Tolerance	O_3 Tolerance	NO_2 Tolerance
61	*Pyrus calleryana Decne.*	1	3	2	2	1	2	1	12	1	1	3	3	1		3	
59	*Sophora japonica L.*	1	2	3	2	2	1	1	12	1	1	3	3	2	3	3	3
41	*Mangifera indica L.*	2	3	2	2	1	1	1	12	1	1	3	2	1	3	3	
40	*Koelreuteria paniculata Laxm.*	1	2	2	1	2	1	3	12	2	1	3	3	2	2	2	
33	*Populus tremuloides Michx.*	1	3	2	2	1	2	1	12	2	2	3	1	1	1	1	
32	*Betula papyrifera Marsh.*	1	2	2	2	1	2	2	12	1	2	3	2	1	1	1	
32	*Hibiscus syriacus L.*	1	1	3	2	2	2	1	12		1	3	2	2	2	1	1
32	*Populus simonii Carrière*	1	3	2	2	1	2	1	12	2	2	3	2	1	1		
30	*Salix caprea L.*	1	3	1	2	1	2	2	12		3	3	1	1	1	1	
30	*Ulmus parvifolia Jacq.*	1	2	2	2	1	3	1	12	1	2	2	3	2	1	2	1
29	*Aesculus × carnea Zeyh.*	1	1	2	2	2	2	2	12		2	3	2	1	3		
29	*Phellodendron amurense Rupr.*	1	2	2	2	2	2	1	12	1	1	3	3	3			
28	*Ligustrum lucidum W.T.Aiton*	2	2	2	2	1	2	1	12	1	3	3	2	2	2	3	2
72	*Prunus cerasifera Ehrh.*	1	2	1	2	1	2	2	11	1		1	2	1	2	2	1
52	*Carpinus betulus L.*	1	1	2	3	1	2	1	11	1	2	2	3	2	2	3	1
51	*Malus sylvestris Mill.*	1	2	1	2	1	2	2	11		1	2	2	1	1		
47	*Cercis canadensis L.*	1	3	1	2	1	2	1	11	1	2	3	3	2	2	2	
44	*Acer palmatum Thunb.*	1	1	1	2	2	2	2	11	1	2	3	2	2	2	3	1
41	*Corylus colurna L.*	1	1	2	2	1	2	2	11	1	2	2	3	2	1	3	
40	*Cornus florida L.*	1	2	1	2	1	2	2	11	1	2	2	2	1	3	2	
36	*Catalpa bignonioides Walter*	1	2	2	2	1	1	2	11	1	1	2	3	1	1	1	
34	*Prunus serrulata L.*	1	2	1	2	1	2	2	11	1		3	2	1	2	2	1
34	*Prunus virginiana L.*	1	2	1	2	1	2	2	11	1	1	3	2	1	2	2	1

Table 5. Continued.

Occurrence	Scientific Name	PM$_{2.5}$ Removal Efficiency							Sum	Negative Impact		Suitability for Urban Environment					
		Type	Growth Rate	Height	Crown Density and Texture	Leaf Complexity	Leaf Length	Leaf Characteristic		BVOC Emissions	Pollen Allergy	Soil tolerance	Drought tolerance	Pest and disease Resistance	SO_2 Tolerance	O_3 Tolerance	NO_2 Tolerance
33	*Eriobotrya japonica* (Thunb.) Lindl.	1	2	1	2	1	1	3	11	1	1	3	2	1			
31	*Prunus avium* L.	1	2	2	2	1	2	1	11	1	1	2	1	1	2	1	
30	*Ostrya virginiana* (Mill.) K.Koch	1	1	2	2	1	2	2	11	1	2	2	3	3	2	3	1
29	*Nyssa sylvatica* Marshall	1	1	3	2	1	2	1	11		1	3	3	3	3	3	
52	*Lagerstroemia indica* L.	1	2	1	2	1	2	1	10	1	1	3	3	2	2	3	
33	*Phoenix canariensis* Chabaud	2	1	2	1	2	1	1	10	2	1	3	3	1	3	3	
30	*Syringa reticulata* (Blume) H.Hara	1	2	1	2	1	2	1	10	1	1	2	2	2			

Supporting Material Available

Countries and cities included in this study (Table S1), References used for deriving characteristics of the tree species. This information is available free of charge via the internet at http://www.atmospolres.com.

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