UNIVERSITÄT FÜR BODENKULTUR WIEN
University of Natural Resources
and Life Sciences, Vienna

Master Thesis

Particulate matter accumulation potential of trees

submitted by

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in the framework of the Master programme

Umwelt- und Bioressourcenmanagement

in partial fulfilment of the requirements for the academic degree

Diplom-Ingenieurin

Vienna, October 2022

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Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Date Signature

Acknowledgements

I want to thank my thesis advisors, Boris Rewald and Matthias Steinparzer for the competent and valuable support. Thanks for encouraging words, for pushing me when I got lost in details and for guiding me through the entire learning process.

Thank you, Dominik, Maria, Lauren and Magdalena for supporting me with professional advice related to this work, but above all, for mental assistance and encouragement.

Table of content

Abstract

Air pollution standards are frequently exceeded worldwide and particulate matter (PM) pollution constitutes a serious health risk especially in urban areas. In tackling this problem, trees play a major role, as they are able to filter particulate matter. Since not all trees perform equally, it is relevant which characteristics are helpful in accumulating PM. Besides that, also climatic aspects and pollution level of the ambient air play a role. Several studies have been conducted that measured accumulated PM on tree leaves and compared different tree species in different surroundings. However, a comprehensive and recent overview on the topic is yet missing. Thus, this work will give a qualitative and quantitative overview over past studies, particularly comparing PM accumulation measured on different tree species and as dependent on different experimental and environmental conditions. Results show, that (meta-)data on parameters are incomplete, rendering cross-study comparisons difficult. However, comparisons of the available data illustrate, that PM accumulation is highest in the most polluted surroundings and lowest in rural sites. Regarding accumulation time, most particulate matter was accumulated by trees after ≤5 days without rain. Among tree functional types, evergreen conifers performed best in PM accumulation per leaf surface area. In order to allow the best possible selection of tree species in relation to site and environmental conditions in the future, further research and above all, a uniform documentation and recording of all parameters that might influence accumulation potential is required.

Keywords: particulate matter, filter function, trees, air pollution mitigation, accumulation potential

Kurzfassung

Die Luftverschmutzungsstandards werden weltweit häufig überschritten, und die Feinstaubbelastung stellt vor allem in städtischen Gebieten ein ernstzunehmendes Gesundheitsrisiko dar. Bei der Bewältigung dieses Problems spielen Bäume eine wichtige Rolle, da sie in der Lage sind, Feinstaub zu filtern. Da nicht alle Bäume die gleiche Leistung erbringen, ist es relevant, die Eigenschaften, welche hilfreich bei der Ansammlung von Feinstaub sind, zu kennen. Darüber hinaus spielen auch klimatische Bedingungen und der Verschmutzungsgrad der Umgebungsluft eine Rolle. Bisher wurden mehrere Studien durchgeführt, in denen die akkumulierte Menge an Feinstaub auf Baumblättern gemessen und verschiedene Baumarten an unterschiedlichen Standorten verglichen wurden. Ein umfassender und aktueller Überblick über das Thema steht jedoch noch aus. Daher liefert diese Arbeit einen qualitativen und quantitativen Überblick über vergangene Studien, insbesondere einen Vergleich der an verschiedenen Baumarten gemessenen Feinstaubmenge in Abhängigkeit von verschiedenen Versuchs- und Umweltbedingungen. Die Ergebnisse zeigen, dass die (Meta-)daten zu den Parametern unvollständig sind, was einen studienübergreifenden Vergleich schwierig macht. Ein Vergleich der verfügbaren Daten zeigt jedoch, dass die akkumulierte Feinstaubmenge in den am stärksten verschmutzten Gebieten am höchsten und in ländlichen Gebieten am niedrigsten ist. Was die Akkumulationszeit betrifft, so wurde die größte Feinstaubmenge nach ≤5 Tagen ohne Regen von Bäumen akkumuliert. Unter den funktionalen Baumgruppen schnitten die immergrünen Nadelbäume hinsichtlich der akkumulierten Feinstaubmenge pro Blattfläche am besten ab. Um in Zukunft die bestmögliche Auswahl der Baumarten in Bezug auf Standort- und Umweltbedingungen treffen zu können, bedarf es weiterer Untersuchungen und vor allem, einer einheitlichen Dokumentation und Erfassung aller Parameter, die das Akkumulationspotenzial beeinflussen könnten.

Stichworte: Feinstaub, Filterfunktion, Bäume, Luftreinhaltung, Akkumulationspotential

1. Introduction

Exposure to air pollution can have adverse effects on human health and especially adverse effects of particulate matter (PM) are well documented. Increased PM levels pose risk to the cardiovascular system, metabolism, airways and the nervous system. According to WHO, life expectancy due to PM exposure is on average reduced by nine months (WHO Regional Office for Europe, 2013). Particulate matter is a heterogeneous mixture of liquid and solid components and includes primary and secondary particles, the latter result from gaseous precursors such as sulphur oxide, nitrogen oxide and ammonia. Particulate matter can be assigned to different size classes according to aerodynamic diameter, namely coarse dust PM_{10} (2.5-10 μm), fine dust $PM_{2.5}$ (2.5-0.2 μm) and ultrafine dust $PM_{0.2}$ (<0.2 μm). Particulate matter emissions originate from combustion processes (heating, oven, engines), traffic (brake dust, tyre wear particles), metal and steel industry, agriculture (ammonia, as a PM precursor) and soil erosion (Umweltbundesamt, 2021).

Besides measures to reduce emissions, particulate matter concentrations can be tackled by decreasing particle concentration in the air. In doing so, the filter function of vegetation, especially of trees, can play an important role (Galk, 2012). On the other hand, trees can also negatively affect air quality by emitting biogenic volatile organic compounds (BVOCs), which favour the formation of ozone, secondary organic aerosols and PM (Fitzky et al., 2019). Additionally, primary organic compounds such as pollen are released (Grote et al., 2016). However, foliage of trees provides enlarged contact area and therefore space for the deposition of particles (Gorbachevskaya et al., 2007). Size and structure of tree crowns lead to turbulent air movement and enhance PM deposition on leaves (Sæbø et al., 2012). Although bole and branch surfaces can even exceed the relative accumulation capacity of leaf surfaces (Xu et al., 2019), their total surface area is comparably low. For this reason, most studies focus on accumulation on the foliage.

Particulate matter can be removed from the troposphere either by wet, dry or occult deposition (Ottelé et al., 2010). Wet deposition means that particles are washed out from the atmosphere with precipitation and spread over different surfaces. Dry deposition refers to particle settling on surfaces (Samson et al., 2017). Occult deposition occurs, when plant organs have direct contact with fog, mist or clouds—removing particles from the air.

Several mechanisms for particle deposition exist. Sedimentation occurs when particles move to foliage surface due to gravitation over a certain period of time. If particles move under the influence of wind and collide with obstacles, they follow the mechanism of impaction. Particles that are close to surfaces can also intercept with them or electrostatic forces can attract them. Ultrafine particles ($PM_{0.2}$) are usually hardly affected by gravitational forces but move to foliage by Brownian motion (Cai et al., 2017; Räsänen, 2017). Both adaxial and abaxial leaf surface collect PM, however, according to Mo et al. (2015) the adaxial surface is on average more effective.

PM that is deposited on the leaf surface may contain lipophilic organic pollutants and can therefore penetrate the wax layer. Particles with a smaller diameter are more likely to penetrate the waxy tissue of leaves than particles with a larger diameter. Terzaghi et al. (2013) found that particles with a diameter >10 µm can hardly be found in the wax layer. Popek et al. (2013) who gravimetrically analysed the mass of deposited PM on 13 different woody broadleaf species concluded that surface PM and in-wax PM contributed about 60% and 40% to total PM (0.2-100 µm) load, respectively. Mo et al. (2015), who sampled 35 species of trees and shrubs, found on average 13% of total PM (0.2-100 µm) to be trapped in wax. PM that is trapped in waxes is removed by litterfall, whereas PM on the surface can be resuspended by wind (Pullman, 2008). However, before being resuspended, some parts of the captured particles can be washed off from leaves with rain and are either resuspended from the ground or immobilized in the soil (Ysebaert et al., 2021). When being deposited on the ground, organic components of PM are decomposed and inorganic components are accumulated in the soil and soil solution (Dzierżanowski et al., 2011).

The amount of PM that is filtered by trees thus depends on several factors which can be divided into climatic aspects, site specific aspects and tree species-specific traits (Figure 1).

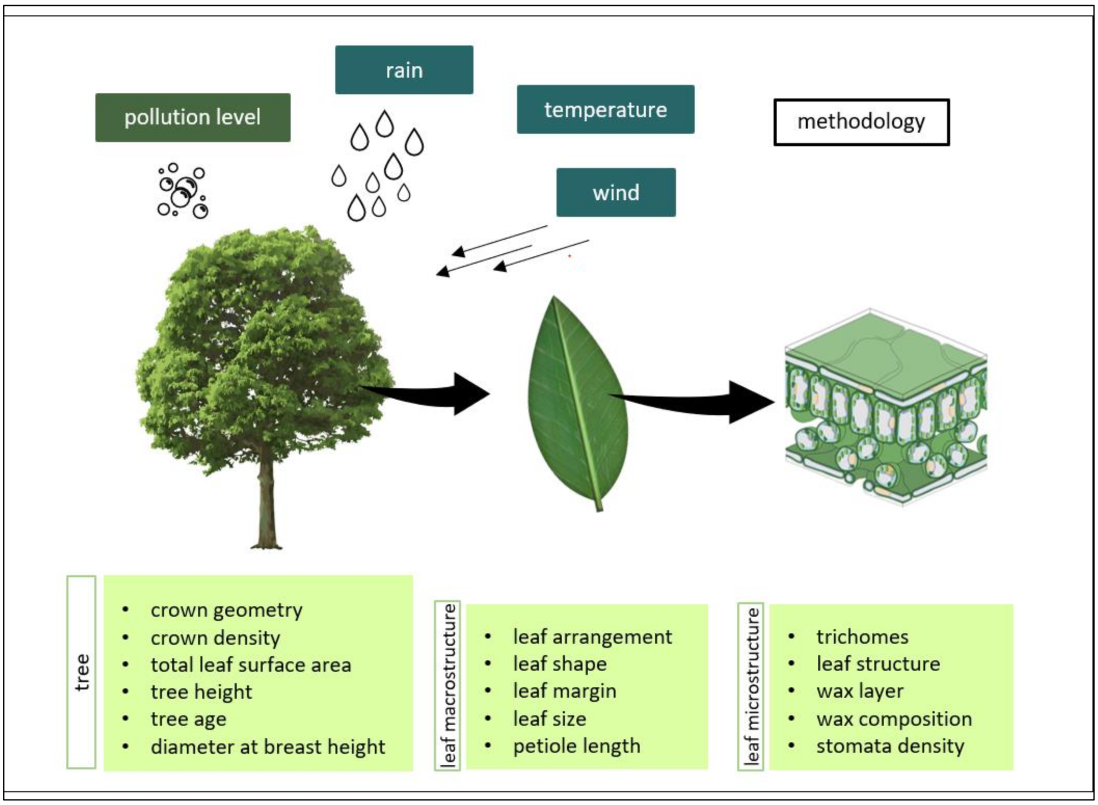

Figure 1: *Abiotic and biotic factors influencing particulate matter accumulation potential. Abiotic factors comprise e.g., pollution level, time and amount of rainfall events, temperature, and wind speeds. Biotic factors are subdivided into three effect level: whole tree traits, and macro- or microstructural leaf traits. Methodology affects the measurements of PM accumulation potentials, see Supplementary methods for an overview.*

The impact of weather depends largely on specific local conditions. Strong wind and heavy rain are more likely to remove PM from foliage surface. Lighter rain and weaker wind on the other hand may foster PM accumulation on vegetation as leaves become "stickier" when being wetted (Popek et al., 2019). The largest PM fraction is easier removed by wind and precipitation, than smaller fractions (Popek et al. 2019). Amount of precipitation and number of days without rain before sampling date play an important role when it comes to measuring PM amount on leaves. Rainfall events are a precondition to enable particle removal over a longer period, as they clean the leaf surface and provide space for new particles. Long dry periods on the other hand, lead to a high resuspension rate and a concomitant decreased in net PM removal (Pace & Grote, 2020).

Apart from that, also temperature is connected to PM accumulation. Although it is hardly evaluated in empirical studies, some authors mention a relationship between temperature and accumulation potential (Pace & Grote, 2020). A high temperature of the ambient air could lead to increased air pollution levels as production of volatile organic compounds is increased, which can react to secondary aerosols (Selmi et al., 2016; Pace & Grote, 2020). On the other hand, with higher temperatures, stomata tend to be open and with that ultrafine particles are more likely to enter the leaves through stomata (Cai et al., 2017).

Besides weather, sampling sites can be roughly divided into urban, periurban and rural sites. They tend to differ in terms of degree of pollution and therefore influence deposition rates. Pollution level of the ambient air, however, can also vary over very small areas, depending on local emission sources, windspeed and wind direction (Popek et al., 2019). Furthermore, pollution level differs between seasons and even during the day. In temperate regions, PM levels rise during the cold season as heating is a major source of PM (Lu et al., 2018). Several studies conclude that PM accumulation amount on foliage surface varies with pollution level (Baldacchini et al., 2019; Hofman et al., 2014). For example, Li et al. (2019) measured the accumulated amount of PM for several species on different sites within one city and determined differences up to 6 to 8-fold between sites. However, more recently Cao et al. (2022) did not find a correlation between pollution level and PM load, arguing that this is because PM saturation is reached before precipitation, at least in heavy polluted regions.

In addition to (micro-)climatic conditions, tree specific aspects influence the PM accumulation amount. Several studies compared accumulated PM amount of different trees species or tree functional types (He et al., 2020; Mo et al., 2015; Thao et al., 2014). Sæbø et al. (2012) found 10-20-fold differences in accumulated PM between different species in their research. These differences can be largely attributed to plant species-specific traits.

At a whole tree level, several aspects influence the amount of PM accumulation (Figure 1). First of all, crown geometry and crown density are crucial. Referring to the crown geometry, the total leaf surface area is relevant, as a large leaf area also provides ample space for PM accumulation. In general, the total leaf area increases with the growth of the tree and is thus related to the diameter at breast height, the height of the tree and the tree age (Liu et al., 2015). Anyway, it should be noted, that the amount of accumulated PM per tree has to be distinguished from the amount of accumulated PM per leaf area. The shape and architecture of the crown affects the turbulence of the airstream and with that residence time of the air and distribution of particulate matter (Grote et al., 2016).

On a leaf level, attributes that are considered by several studies are leaf shape, leaf size, leaf blade margin and petiole length. The effect of this characteristic is closely related to movement in the airstream and with that PM dislodgement (Leonard et al., 2016; Samson et al., 2017). Elliptical and linear leaves for example bend with the wind flow, do not swirl the airstream too much, thus being less effective in PM capturing than needle leaves with their rigid nature (Weerakkody et al., 2018). Considering microstructural properties, the complexity of leave leaf structures, coarseness and hairiness are decisive. A coarse leaf structure with many grooves and ridges enables capturing of particles (Zhang et al., 2019). Trichomes seem to have positive effects on PM accumulation (Chen et al., 2017; Mo et al., 2015; Sæbø et al., 2012). These hairy structures increase surface area and decrease the probability that particles are dislodged, when the leaves are moving (Zhang et al., 2019). In addition, higher wax amount and chemical composition of the wax layer are known to positively influence PM deposition (Sæbø et al., 2012). Considering stomata, results are ambiguous. While some scientists (e.g., Mo et al., 2015) consider a low stomata density to foster PM accumulation, others argue that stomata enhance coarseness of the leaf surface and therefore increase PM accumulation (Sgrigna et al., 2020). It also has to be taken into consideration that $PM_{0.2}$ can pass through stomata and enter plants (He et al., 2020).

Concerning aforementioned leaf traits, characteristics can change during the season or with the age of a tree or a leaf, such as hairiness, composition and amount of cuticular waxes, or tree architecture. Moreover, stress such as drought, pests and diseases can have effects on tree health and with that on appearance of tree and its traits (Samson et al., 2017). Furthermore, accumulated PM amount can vary within one tree crown, depending on exposure to pollution source, wind and rain and leaf traits, which can differ within the canopy (Hofman et al., 2014). Subsequently, certain parameters are interacting and influencing each other. The effect of wind and rain, for instance, depends on plant morphological characteristics and the composition and structure of the leaf's wax layer (Popek et al., 2019). Thus, the consideration of combined leaf traits on PM accumulation might be more relevant than focusing on single traits (Leonard et al., 2016; Popek et al., 2019).

Finally, the applied methodology has an influence on the measured amount of accumulated PM. Particulate matter accumulation can be determined for example by deposition velocity, particle cover area or by leaf saturation isothermal remnant magnetization, as well as by determining the deposited amount per leaf area (µg cm^{-2}) gravimetrically or by counting particle number per leaf area (N mm^{-2}) by SEM method. These methods hold certain advantages and drawbacks, and derived PM values depend on the type of measurement; details on the methodologies are given in the Supplement.

In light of the above discussed parameters influencing filter functions, it becomes evident that quantifying the accumulation potential of trees is complex. This thesis thus aims for providing a concise overview on the state-of-the-art on PM accumulation and filter function of trees by means of a bibliometrical overview and a meta-analysis. In specific, the following research questions will be addressed:

1) Under which circumstances has the filter potential of trees been measured so far and which methods have been applied to estimate accumulated PM amounts on foliage?

2) Which abiotic and biotic factors influence the amount of accumulated PM on foliage?

To answer the research questions, data from 57 papers covering 11 countries and 190 species in the years 1996-2019 were extracted. PM accumulation per size class was compared in a meta-analysis regarding the parameters pollution level, sampling site, days without rain before sampling, and tree functional types.

2. Methods

2.1. Data collection and preparation

Literature research for the meta-analyses was conducted in Google Scholar, Boku Lit Search and Semantic Scholar. Furthermore, cited papers of already collected papers were studied and key authors were identified. In order to ensure that the database is as comprehensive as possible, the tool connected papers (Eitan et al., 2022) was used, which enables a graphical presentation of all similar studies. Keywords that were used are ”Particulate Matter“, ”PM“, ”Accumulation“, ”Filter“, “Vacuum Filtration”, “Tree“, “Foliage“, and “Filter function“. Literature research for inclusion in the meta-analysis was conducted until 31.12.2021. In total 57 studies were selected (Supplementary Table S1), giving PM deposition amount per leaf area (µg cm^{-2}) or particle number per leaf area (N mm^{-2}).

2.2. Year and country of publication

The large majority of the integrated papers were conducted in China (n=24), followed by Poland (n=11) and Italy (n=6, Figure 2A). Although important research on filter function of trees were conducted in the United States by Nowak et al. (2014) these publications were not integrated into this master thesis as values do not refer to PM load per surface area but on PM removal per area of tree cover, which was not part of this thesis. Figure 2B illustrates, that most of the selected studies were published in the last ten years.

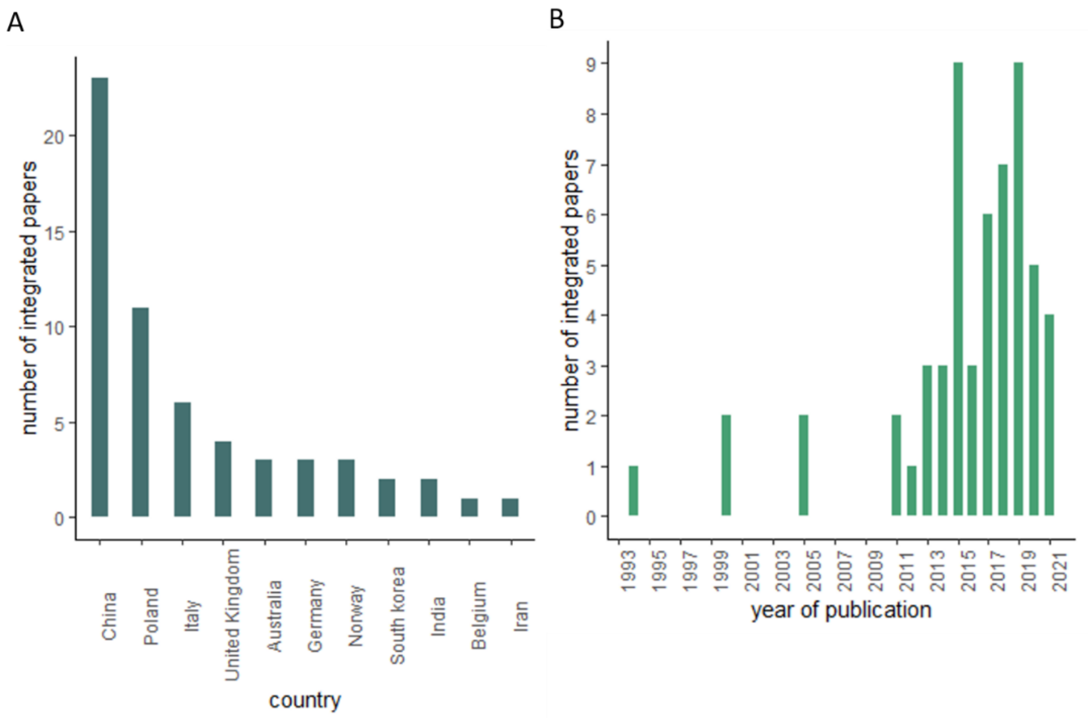

***Figure 2**: Information on the studies selected for this meta-analysis, with A) the number of studies per country and B) the number of studies per year.*

Data were extracted directly from tables or were estimated from figures in the publications. In case PM classes were chosen differently, data was associated with the nearest class (e.g., PM 1.6-10 into PM 2.5-10). Data as well as parameters were collected in an excel sheet. Tree species were divided into the functional categories "evergreen conifers (EC)", "deciduous conifers (DC)", "deciduous broadleaves (DB)", and "evergreen broadleaves (EB)". *Ginkgo biloba* as a phylogenetically distinct species was assigned to the category DB for simplification.

2.3. Statistical analyses

Statistical analyses were performed in RStudio 4.1.1. (R Core Team, 2021). For a first overview on the data on PM load (µg cm^{-2}) and particle number (N mm^{-2}) histograms were plotted and normal distribution was checked graphically with QQ-plots as well as with Shapiro-Wilk-test. As data was not distributed normally, even after attempted transformation of data, the Kruskal–Wallis non-parametric test and Dunn's non-parametric pairwise comparison were applied to test for significant differences between different groups regarding amount of accumulated PM. Tests were conducted to evaluate differences between pollution-level, accumulation period and categories of tree. As data on pollution level was quite sparse (Figure

3) also sampling site was used as a parameter. Due to the low amount of data, comparisons of particle number (N mm^{-2}) in terms of pollution level and groups of days without rain before sampling, are not given in the results.

To determine correlations between surface PM and wax-embedded PM, a subset of papers was selected that included both values. As it was assumed that SEM method only allowed to measure particle number on the surface of the leaves but not in the wax-layer (Yan et al., 2016), only data on PM load (µm cm^{-2}) were selected for analyses. As data was not distributed normally, Kendall's correlation test was conducted.

7. Metadata given on study subject and environmental conditions

This chapter provides an overview on the setting of the studies analysed for this thesis, split into the four categories climate, measurement, sampling tree and site (Figure 3).

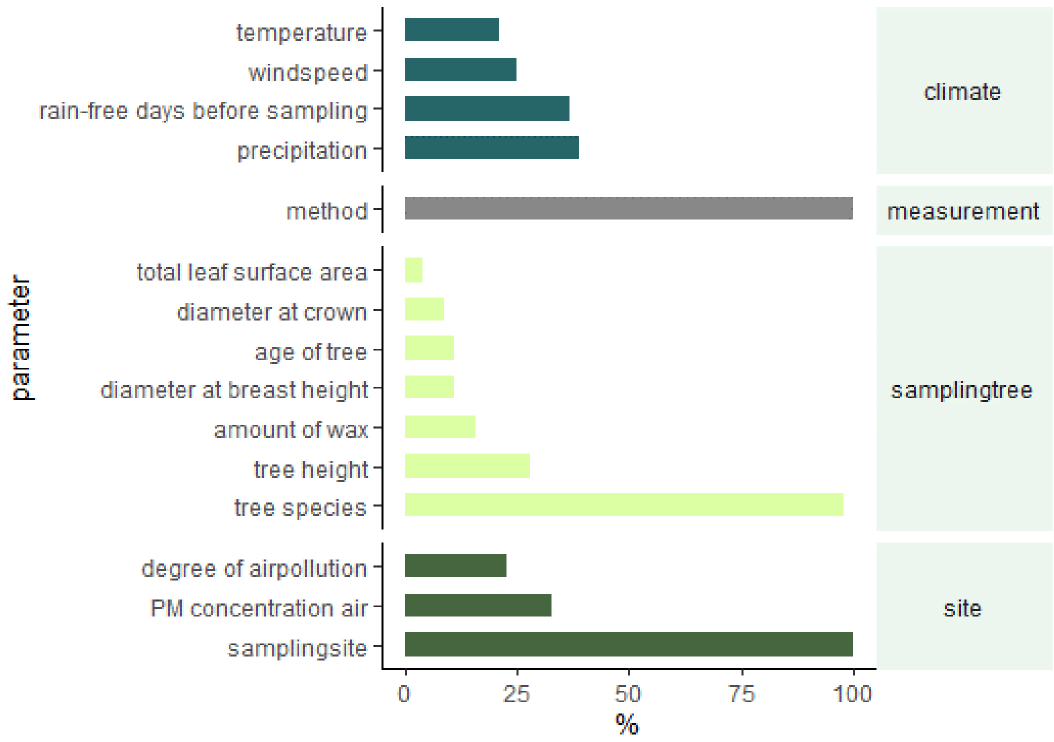

Figure 3*: Percentages of papers integrated in this meta-analysis that contain certain information regarding (micro-)climate conditions, measurement methodology, traits of sampling trees and site characteristics incl. levels of air pollution and site location within a rural-urban gradient.*

7.1. Data on climate and edaphic conditions

Despite the fact that (micro-)climatic aspects play an important role when it comes to PM accumulation on the tree leaves, data on weather conditions before and during sampling are frequently rudimentary. Less than half of the papers report data on precipitation, windspeed and temperature. Additionally, the duration of the specified period of measurement varies. Some papers refer to the day of sampling, others to monthly or annual means. Rain-free days before sampling is related to the accumulation period, but was not documented very often. Moreover, the statements in this regard were vaguely formulated and minimum values rather than exact numbers of days were given. Soil conditions were only mentioned in one study (data not shown) and were thus omitted from further consideration.

7.2. Data on measurement procedures

The methods of data collection were described in all considered studies, although the levels of details vary. While some authors described the laboratory procedures very precisely, others left out information on the leaf side (e.g., abaxial, or adaxial) evaluated or the exact range of size classes taken into consideration. In brief, methods applied by the integrated studies can be divided into field-experimental studies (n=50), modelling studies/literature studies (n=2) and laboratory studies (n=5). The field-experimental studies can be further divided into studies using the gravimetrical method for analyses, which gives the amount of PM on surface and epicuticular wax (µg cm^{-2}), and those using the SEM/EDX methods, which provide the number of particles on the surface (N mm^{-2}). Further information on the methods applied are provided in the Supplement.

7.3. Data on sampling tree

Although several scientists emphasise on the relevance of micro- and macrostructural leaf and tree traits (see introduction) many papers lack data on sampling tree characteristics. While 98% of the papers named the studied tree species, less than 30% of studies gave information of tree height and amount of wax on the leaves. Only about 10% of the studies provided information on age of sampling tree, diameter of crown, diameter at breast height, and total leaf surface area. Some authors stated that healthy trees were samples, but in general eco-physiological condition of trees were hardly mentioned.

7.4. Data on site

All integrated studies give information on the sampling site. Apart from information on country and city, most studies also describe the surroundings of the sampling site. However, it is difficult to categorize this data on the site and compare it with each other. Data pertaining pollution level was quite sparse. Some studies compared foliage of sampling location with different pollution levels, but information on PM concentration trend of the ambient air of the days before sampling date was hardly available. Most studies lack information on PM concentration or only give information on annual means. It should be noticed that ambient air PM concentration varies on a spatially small scale, as particular sources of emission, such as busy roads or industrial companies, can have significant effects on pollution level (Merbitz, 2013).

8. Influence of abiotic and biotic parameters on PM accumulation

The following subchapters show results of analyses regarding impact of certain abiotic and biotic parameters on accumulated PM in terms of mass and particle numbers. Moreover, results on correlation analyses between surface PM and wax-embedded PM are presented.

8.1. Effects of sampling locations and environmental factors on PM accumulation

8.1.1. Pollution level

A Kruskal-Wallis test showed that all PM-fractions had significant differences of PM amount between groups of pollution level. Comparison of groups by Dunn's multiple comparison showed that $PM_{0.2}$ accumulation was significantly higher in areas with a high pollution level compared to those with a low pollution level ($p < 0.001$) (Figure 4; Supplement Table S2). $PM_{2.5}$ load also differed significantly between groups of pollution level ($p < 0,001$). $PM_{2.5}$ was significantly higher at areas with a high pollution level and medium pollution level compared to areas with a low pollution level. Both PM_{10} and $PM_{>10}$ values were significantly higher at high polluted areas compared to medium and low polluted areas (PM_{10} ($p < 0.001$) $PM_{>10}$ ($p < 0.001$)).

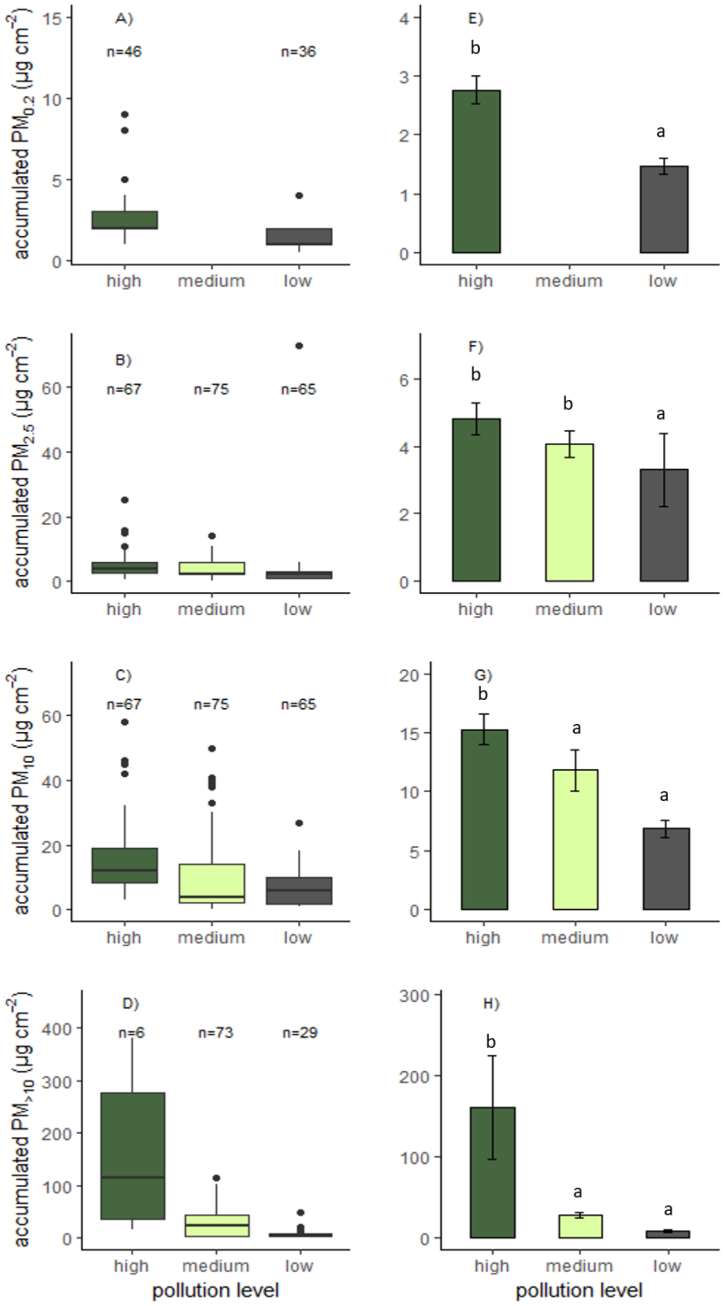

Figure 4: *Effect of pollution level on accumulated PM load in µg cm^{-2}* ***A-D****) Box plots show 1st and 3rd interquartile range with line denoting median and outliers are represented by dots.* ***E-H****) Bar plots represent mean ± standard error. Letters indicate statistically significant differences among groups ($p < 0.05$, Kruskal-Wallis and Dunn's multiple comparison tests; sample number n is given per PM size class and pollution level).*

8.1.2. Sampling site

Accumulation of all four PM-fractions were significantly influenced by sampling site (Figure 5; Supplement Table S3). $PM_{0.2}$ differed significantly between groups (p < 0.001) with periurban sites (median = 3 µg cm^{-2}) showing highest amount of PM followed by rural sites (median = 1 µg cm^{-2}) followed by urban sites median = 0.33 µg cm^{-2}).
$PM_{2.5}$ load also showed significant differences (p < 0.001). $PM_{2.5}$ amount was significantly higher at periurban sites (median = 3 µg cm^{-2}) than at urban sites (median = 2.8 µg cm^{-2}) $PM_{2.5}$ amount at rural sites (median = 2 µg cm^{-2}) was significantly lower than at urban sites. PM_{10} load differed significantly (p < 0.05) between periurban (median = 8 µg cm^{-2}) and rural sites (median = 6 µg cm^{-2}) whereas periurban sites showed higher PM_{10} amounts. $PM_{>10}$ also differed significantly between sampling site (p < 0.01). $PM_{>10}$ load was significantly higher at urban sites (median = 17 µg cm^{-2}) compared to periurban sites (median = 13.72 µg cm^{-2}). Periurban sites where significantly higher than rural sites (median = 5.5 µg cm^{-2}). Apart from $PM_{0.2}$, trees on rural site accumulated the lowest amount of PM of all size fractions. It has to be noticed that the order of median values and mean values is not always the same, which can be explained by outliers above, that move the mean to a higher value.

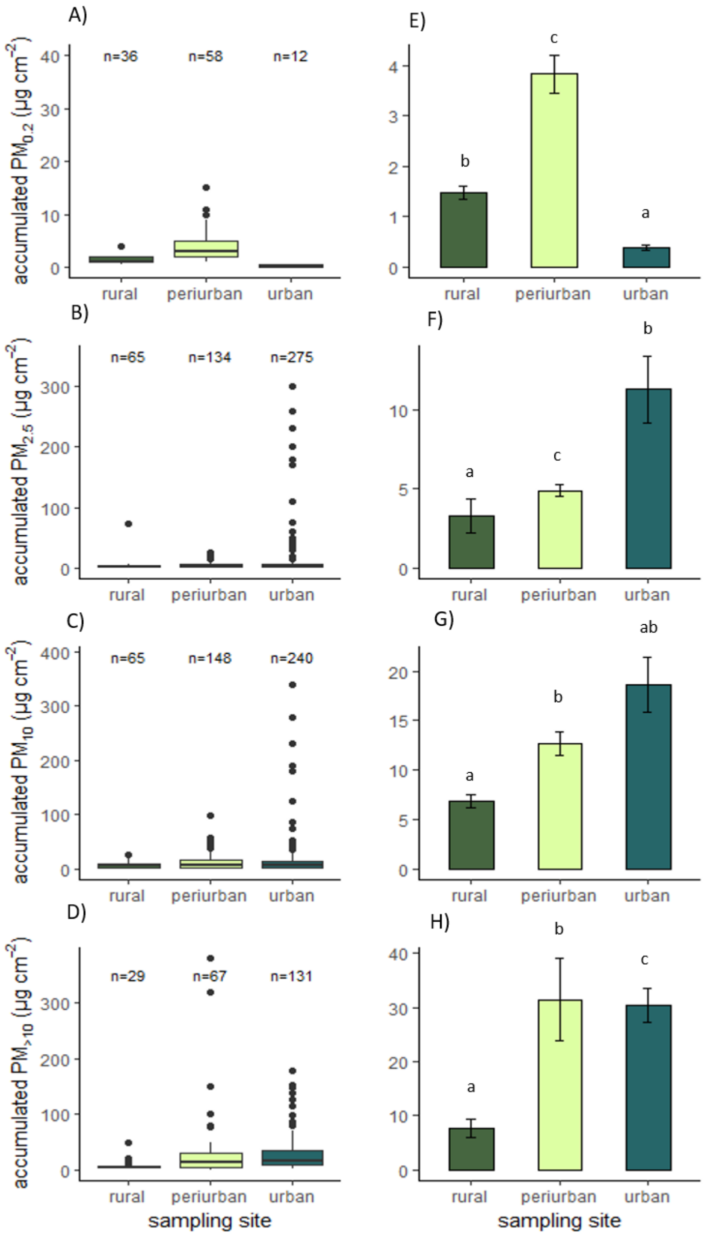

Figure 5: *Effect of sampling site on accumulated PM load in µg cm^{-2}* ***A-D****) Box plots show 1st and 3rd interquartile range with line denoting median and outliers are represented by dots.* ***E-H****) Bar plots represent mean ± standard error. Letters indicate statistically significant differences among groups (p < 0.05, Kruskal-Wallis and Dunn's multiple comparison tests; sample number n is given per PM size class).*

Regarding particle number, there was no data available for rural sites, therefore only periurban and urban sites were compared (Figure 6; Supplement Table S4). The number of particles of all four size fractions was significantly higher at urban sites compared to periurban sites ($PM_{0.2}$ (p < 0.05) $PM_{2.5}$ (p < 0.01) PM_{10} (p < 0.001) $PM_{>10}$: (p < 0.001)) (Figure 6; Supplement Table S4). Median of particle number of $PM_{>10}$ at urban sites (400 N mm^{-2}) represented only a small fraction of the median of particle number of $PM_{0.2}$ (10500 N mm^{-2}) at urban sites. The same holds true for periurban sites.

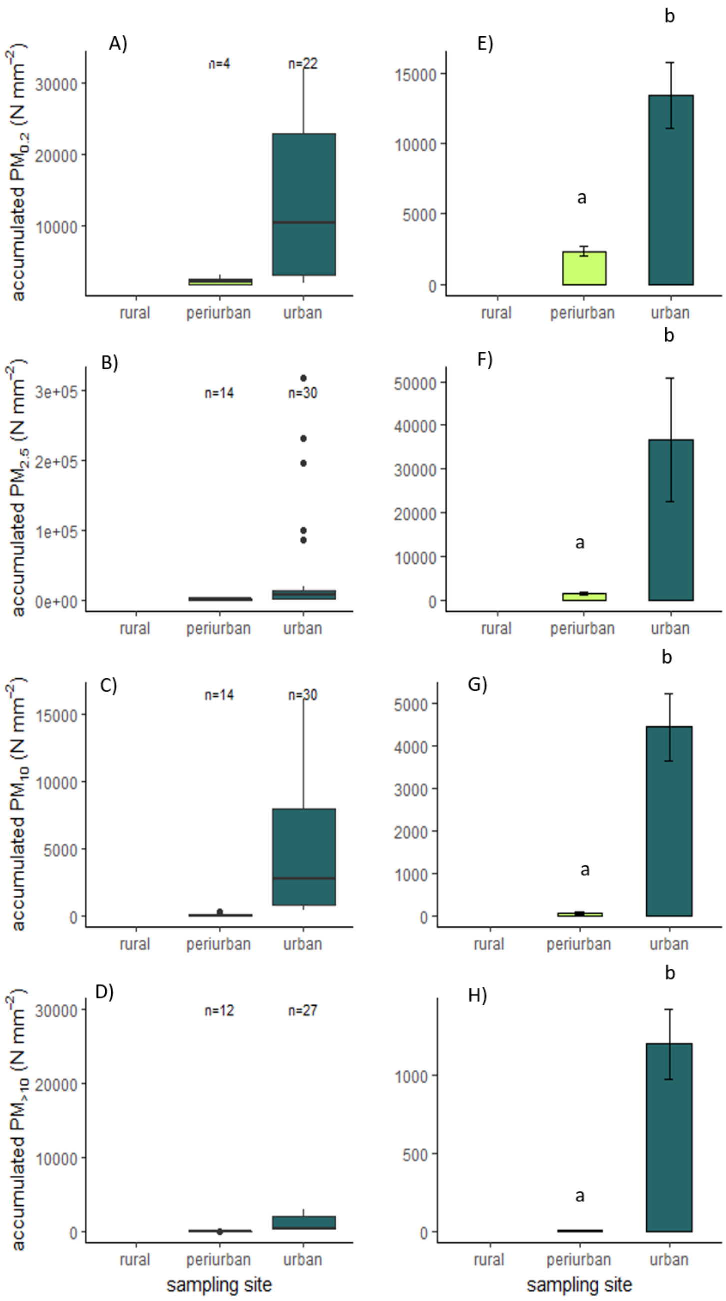

Figure 6: *Effect of sampling site on number of accumulated particles in N mm^{-2}.* ***A-D****) Box plots show 1st and 3rd interquartile range with line denoting median and outliers are represented by dots.* ***E-H****) Bar plots represent mean ± standard error. Letters indicate statistically significant differences among groups ($p < 0.05$, Kruskal-Wallis and Dunn's multiple comparison tests; sample number n is given per PM size class).*

8.1.3. Days without rain before sampling

Significant results appeared within $PM_{2.5}$ regarding different groups of days without rain before sampling (p < 0.001) (Figure 7; Supplement Table S5). $PM_{2.5}$ load was significantly higher when taking samples after up to 5 days without rain (median = 30 µg cm^{-2}) than on foliage with 6-15 days without rain (median = 2 µg cm^{-2}) or more than 16 days without rain (median = 1.83 µg cm^{-2}). PM_{10} load differed significantly between groups (p < 0.001) whereas PM load was significantly higher at group ≤5 days without rain (median = 30 µg cm^{-2}) than at group ≥16 days without rain (median = 7.85 µg cm^{-2}) which was again significantly higher than 6-15 days without rain (median = 3.9 µg cm^{-2}). Moreover, also $PM_{>10}$ differed significantly between groups ≤5 days without rain (median = 46.36 µg cm^{-2}) and group 6-15 days without rain (median = 14.87 µg cm^{-2}) (p < 0.01). In sum, the tree group with ≤5 days without rain prior sampling showed the highest median PM accumulation across all size fractions.

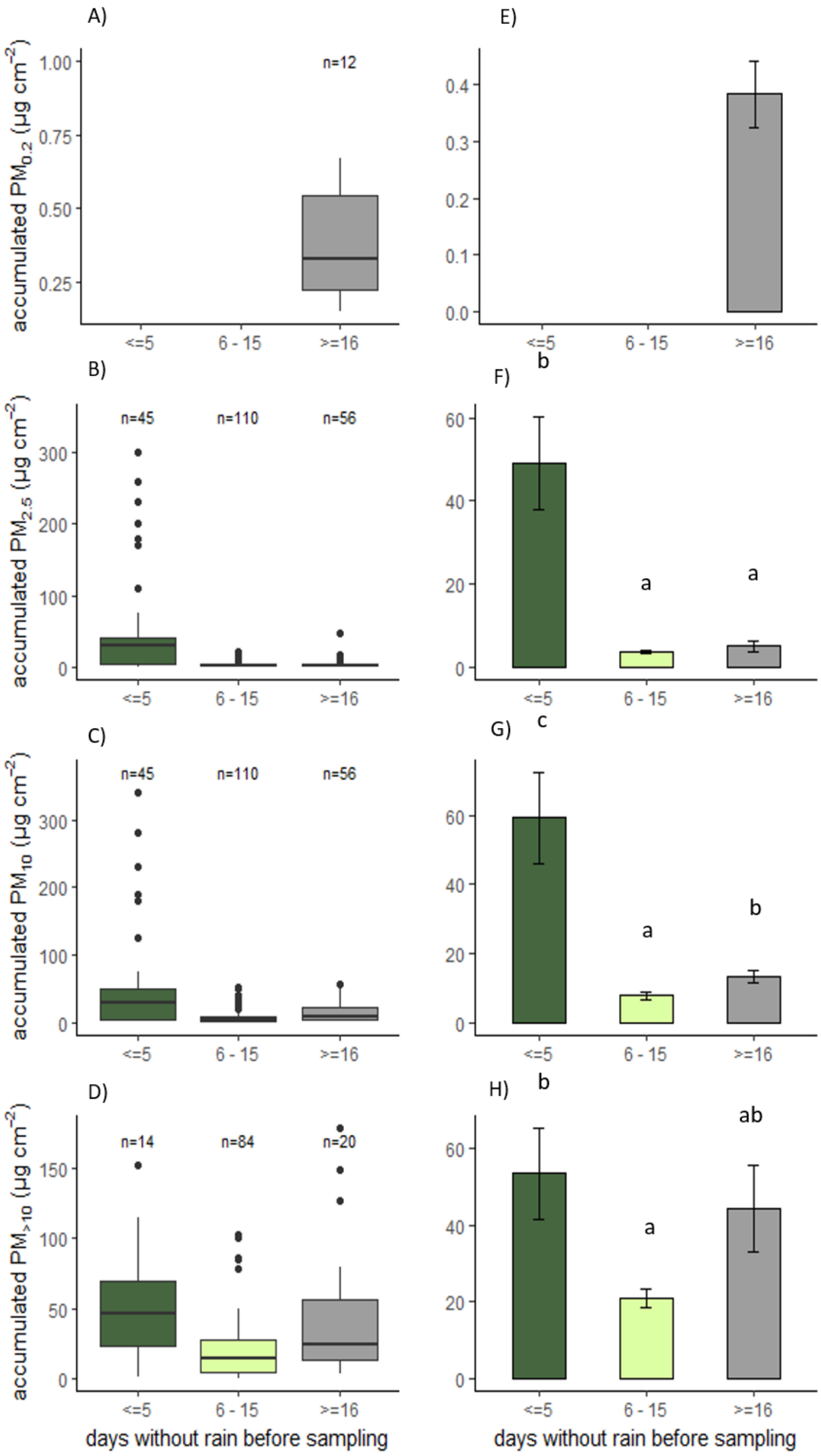

Figure 7: *Effect of days without rain before sampling on accumulated PM load in µg cm*$^{-2}$ ***A-D****) Box plots show 1st and 3rd interquartile range with line denoting median and outliers are represented by dots.* ***E-H****) Bar plots represent mean ± standard error. Letters indicate statistically significant differences among groups (p < 0.05, Kruskal-Wallis and Dunn's multiple comparison tests; sample number n is given per PM size class).*

8.2. Effects of tree functional type on PM accumulation

Comparison of measured PM load on different categories of tree by Kruskal-Wallis-test shows that significant differences occur within all four size classes (Figure 8; Supplement Table S6).

Regarding $PM_{0.2}$ comparison of categories of trees revealed significant differences between all four functional groups ($p < 0.001$). Evergreen conifers accumulated significantly more PM than evergreen broadleaves and deciduous-broadleaves. $PM_{2.5}$ values were significantly higher on evergreen-conifers and on evergreen broadleaves compared to deciduous-broadleaves ($p < 0.001$). PM_{10} values were significantly higher on evergreen conifers than on deciduous broadleaves and evergreen broadleaves ($p < 0.05$). $PM_{>10}$ comparison of tree categories showed that evergreen conifers and evergreen broadleaves accumulated significantly more than deciduous broadleaves ($p < 0.001$).

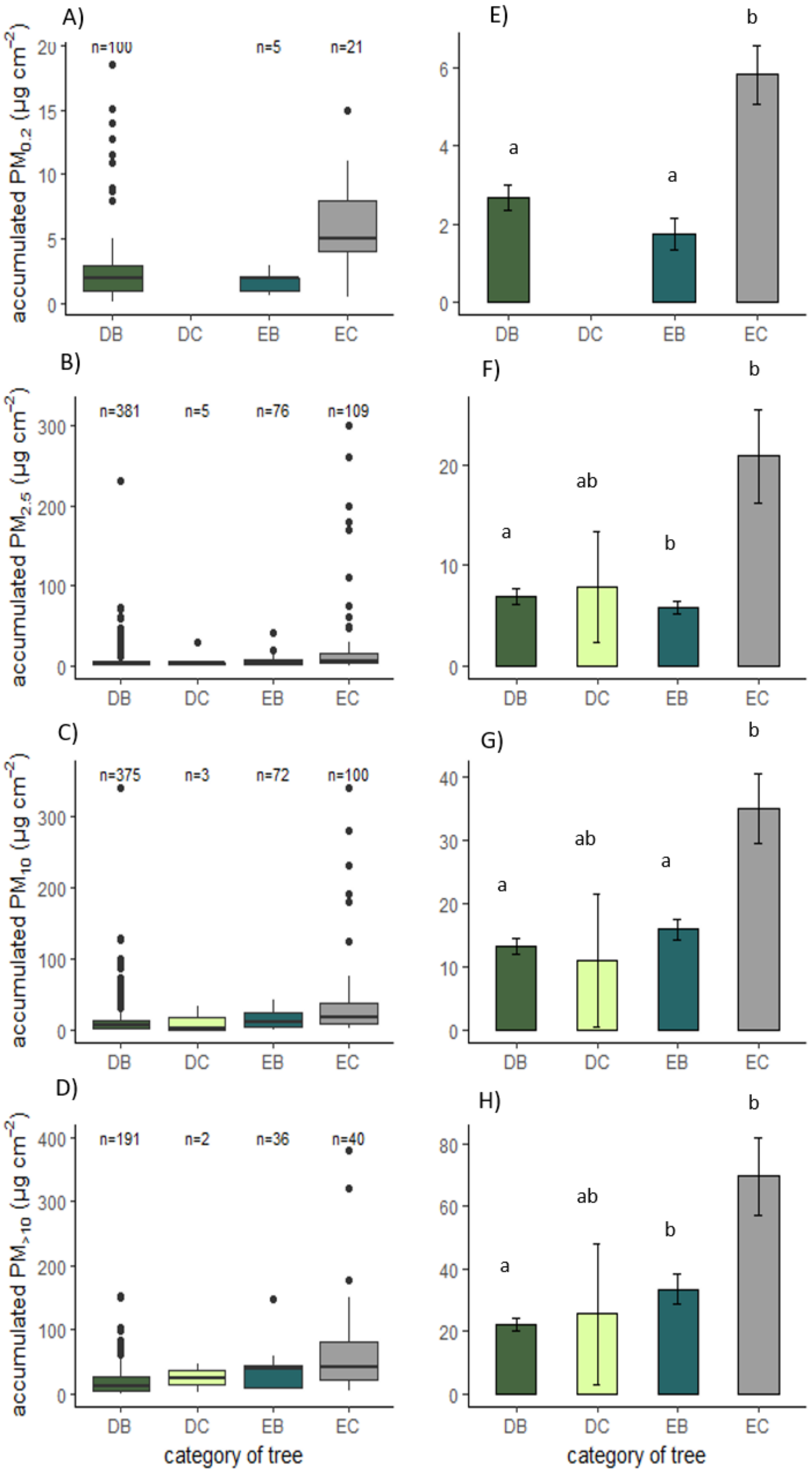

Figure 8: *Effect of tree category on accumulated PM load in µg* cm^{-2} ***A-D****) Box plots show 1st and 3rd interquartile range with line denoting median and outliers are represented by dots.* ***E-H****) Bar plots represent mean± standard error. Letters indicate statistically significant differences among groups (p < 0.05, Kruskal-Wallis and Dunn's multiple comparison tests; sample number n is given per PM size class). Abbreviations: DB, deciduous broadleaves; DC, deciduous conifers; EB, evergreen broadleaves; EC, evergreen conifers.*

Overall, all four fractions have in common that evergreen conifers achieve the highest median and mean (Table S6). As the particle size increases, also accumulated weight increases. Median of $PM_{<10}$ at evergreen-conifers and of evergreen-broadleaves is about 8-folds and about 20-fold higher than the one of $PM_{0.2}$, respectively.

Besides PM load (µg cm^{-2}), also the number of accumulated particles (N mm^{-2}) differed significantly between functional categories of trees (Figure 9, Supplement Table S7).
The number of $PM_{0.2}$ particles was significantly higher on deciduous broadleaves than on evergreen broadleaves ($p < 0.05$). $PM_{2.5}$ comparison of tree categories showed significant differences ($p < 0.01$), i.e. the number of particles on evergreen conifers and deciduous broadleaves were significantly greater than on evergreen broadleaves. Similar results were shown for PM_{10}, with evergreen conifers and deciduous broadleaves exceeding PM accumulated on evergreen broadleaved species significantly ($p < 0.001$). Regarding $PM_{>10}$, deciduous broadleaved trees accumulated significantly more particles than evergreen broadleaves ($p < 0.001$).

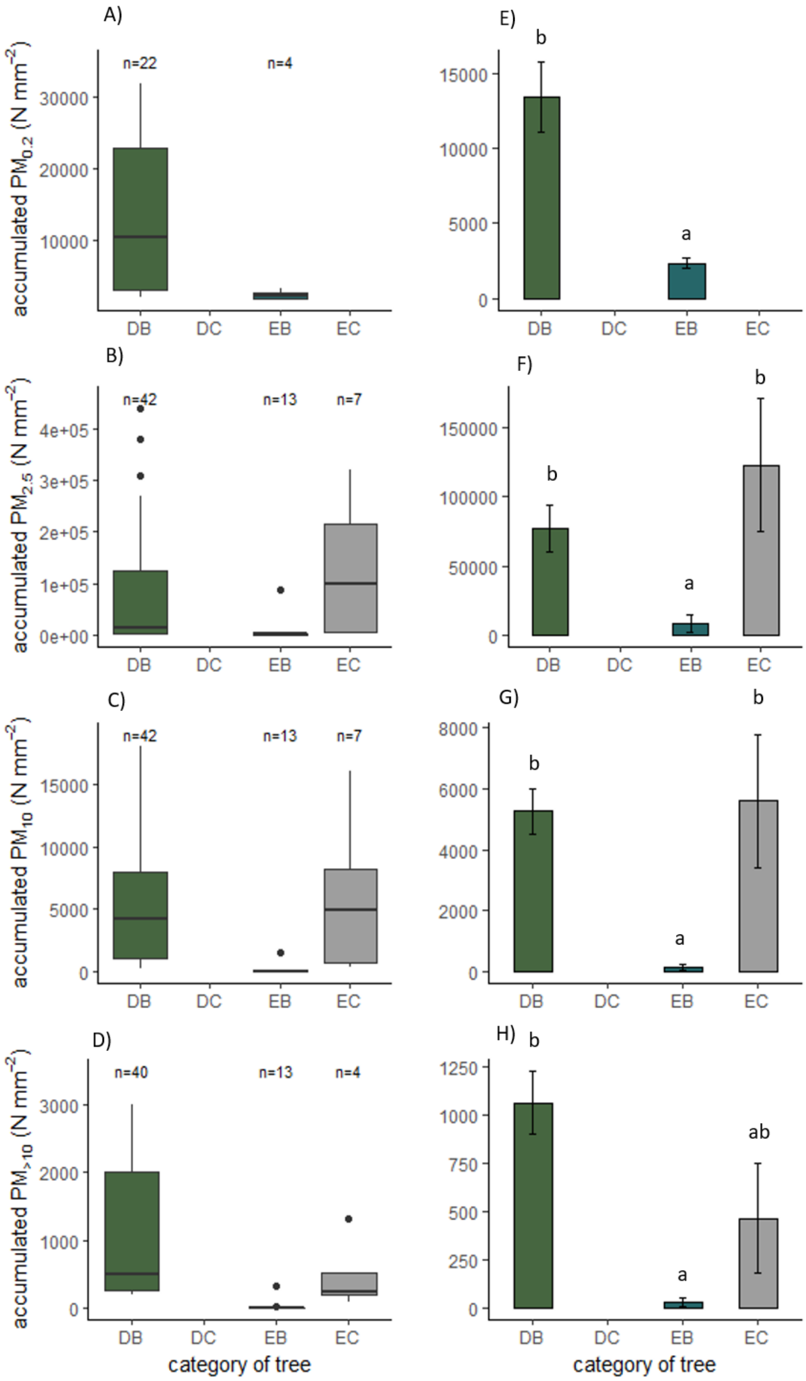

Figure 9: *Effect of tree category on number of accumulated particles in N mm^{-2}.* ***A-D****) Box plots show 1st and 3rd interquartile range with line denoting median and outliers are represented by dots.* ***E-H****) Bar plots represent mean ± standard error. Letters indicate statistically significant differences among groups ($p < 0.05$, Kruskal-Wallis and Dunn's multiple comparison tests; sample number n is given per PM size class). Abbreviations: DB, deciduous broadleaves; DC, deciduous conifers; EB, evergreen broadleaves; EC, evergreen conifers.*

Across all four size classes, evergreen broadleaves accumulated the least number of particles. In contrast to PM load (µg cm^{-2}), the number of particles (N mm^{-2}) tended to decrease with increase of particle size.

9. Correlation of surface PM and wax-embedded PM

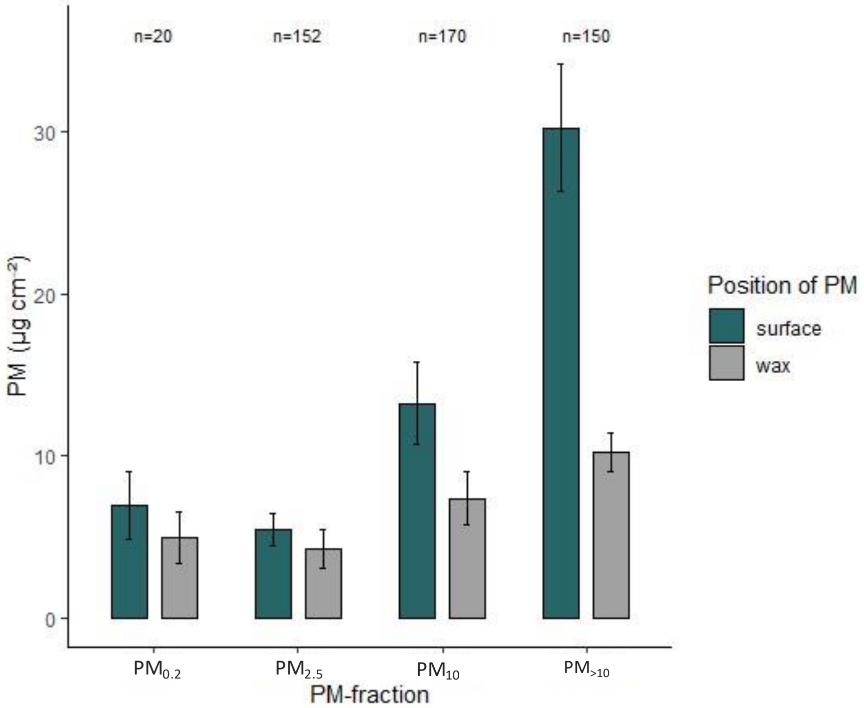

Figure 10: *Comparison of leaf surface particulate matter (PM) and wax-embedded PM amount per PM size fraction, see text for details. Bar plots represent mean values. Vertical bars represent the standard error; N is given*

Comparison of surface PM and wax-embedded PM shows, that PM accumulated on the surface exceeds the amount of PM that was found in epicuticular waxes of all four size classes (Figure 10). What stands out is the higher share of surface PM at larger fractions compared to smaller fractions. For $PM_{0.2}$ almost half of the accumulated amount was found in waxes, whereas for $PM_{>10}$ only about one quarter was embedded in the wax layer.

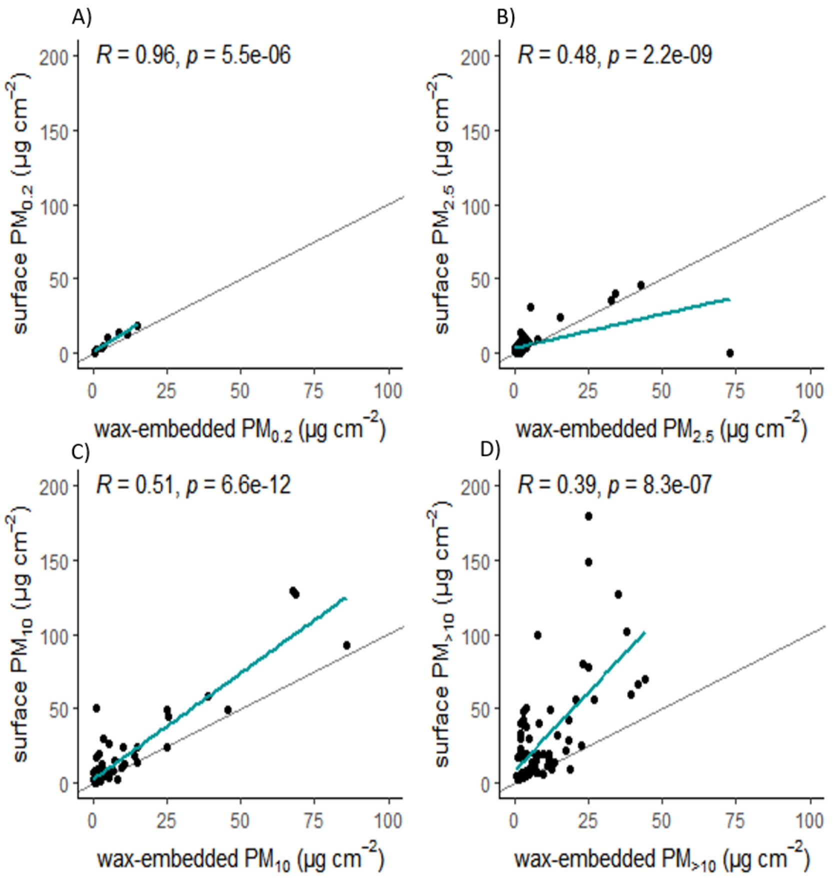

Figure 11: *Correlation between surface particulate matter (PM) load and wax-embedded PM load. R=Kendall's correlation coefficient. A-D) showing correlations of different PM size-classes.*

A significant positive correlation was found between in-wax PM and surface PM of all four size classes (p<0.001) (Figure 11). As the particle fraction size increases, so does the slope of the correlation line. This indicates that the difference in the amount of accumulated PM on the surface compared to the one in the wax is greater for the larger fractions ((PM_{10} and $PM_{>10}$) (Figure 11C) and (Figure 11D)) than for the smallest fraction ($PM_{0.2}$) (Figure 11A)). The correlation of $PM_{2.5}$ size class represents an exception here, showing a smaller slope. This could be attributed to an outlier (Figure 11B)).

6. Discussion

The analyses of the collected data regarding PM accumulation potential of trees allows to determine the most frequently observed parameters and to outline in which way they influence the accumulation amount.

6.1. Impact of sampling location and environmental factors on PM accumulation

The amount of accumulated PM was higher in highly polluted regions compared to low polluted regions. This did not come as surprise as several studies had focused on comparison of different sites showing higher PM loads in more polluted areas (Bui et al., 2022; Lu et al., 2018; Popek et al., 2018). However, it seems that with a certain pollution level, saturation is reached and a higher ambient air PM concentration does not lead to a greater accumulation as the surface and wax layer is somehow “covered“. According to Wang et al. (2015) equilibrium of particle cover area is about 10-50% on the adaxial side and 3-35% on the abaxial side.

However, results regarding sampling site do not fully meet expectations as the rural-urban gradient had been estimated to be loosely related to pollution levels. While particle number (N mm^{-2}) were indeed significantly higher at urban study sites compared to periurban sites, PM load (µg cm^{-2}) was highest at periurban sites. Vague classification could be the reason for this, as especially the differentiation between periurban and urban sites is sometimes unclear. Another explanation could be that periurban sites are in some cases heavier polluted than urban sites, as there might be industrial areas or highways close by or less green infrastructure and with that less foliage surface is available, compared to urban sites.

The different results of particle number (N mm^{-2}) and PM load (µg cm^{-2}) could occur because different studies were included in the analyses depending on availability of targeted values.

Besides pollution level, precipitation plays a key role as it regenerates the leaf's capacity to bind particulate matter (Popek et al., 2019; Zhang et al., 2019). It is therefore reasonable, that information on rainfall is most frequently reported among all (micro-)climatic parameters. To determine total net PM removal, data on annual precipitation and distribution of rain events is important. However, most studies determine the PM load per leaf area through a single measurement in time, instead of a continuous measurement campaign (e.g. Przybysz et al., 2019; Terzaghi et al., 2013; Zhang et al., 2019). Therefore, it is highly relevant when the last rainfall had occurred before sampling took place.

Results regarding the different categories of rain-free days before sampling presented, however, a contradictory picture. Surprisingly, the greatest amount of PM was accumulated on sampling leaves in the class with the lowest number of days (≤5 days) compared to the groups 6-15 days without rain and ≥16 days without rain.

A possible reason could be that wet leaf surfaces are more effective in accumulating PM and resuspension could be limited (Wang et al., 2013). Moreover, it needs to be considered that with the process of wet deposition, raindrops wash out PM from the atmosphere and they might transport them to the leaf surface (Gao et al., 2019)**.** Furthermore, Zhang et al. (2019) report, that amount of PM that is washed off by rain events largely depends on intensity and duration of rainfall and varies between trees species. Depending on rain intensity, a certain amount of PM retains on the leaf surfaces after rain events (Przybysz et al., 2014). This puts the significance of the timespan between rain event and sampling date into perspective. After all, many papers did not report exact number of days without rain, but minimum values and this could distort the classification.

Various environmental parameters, such as temperature, windspeed and moisture are influencing PM accumulation, but could not be statistically analysed in this work. Although they are discussed in the literature (Blanusa et al., 2015; L. Chen et al., 2016; Litschke & Kuttler, 2008), data was not provided in most of the articles included in the meta-analyses. However, several publications (Chávez-García & González-Méndez, 2021; Saenger & Schroeder, 2019) emphasize the importance of airflow. Especially in areas with narrow street canyons, planting density and position of trees to pollution source and wind direction have to be considered as well. Otherwise, pollution levels could be even increased in certain areas if circulation is hindered (Chen et al., 2016). Despite the importance of wind speed, the question arises how to record it, since the temporal and spatial variations of this parameter are considerable.

6.2. Impact of tree functional type

As reported earlier (e.g., Chen et al., 2017; Beckett et al., 2000; Bui et al., 2022), the meta-analysis showed that evergreen conifers performed best regarding PM load. This could be attributed to their rigid leaf structure and thick wax layer (Weerakkody et al., 2018; Barwise & Kumar, 2020). Particle number (N mm^{-2}) on the other hand was not significantly higher on evergreen-conifers. Reason for this could be that the SEM method (see Supplement Methods), which is applied for particle number counting, does not allow to measure wax embedded particles. This could lead to an underestimation of the actual particle number on the needle surface, weakening the positive effect of high wax contents of conifers.

Comparing different tree types regarding their potential to mitigate PM pollution, the measured PM load per leaf area only provides limited information. Rather the performance on a tree level is relevant here. As conifers tend to have larger total leaf surface areas than broadleaved species, chances are higher to accumulate more PM (Liang et al., 2016). Besides total leaf surface area, also the temporal appearance of trees is relevant. While evergreen species are able to mitigate air pollution all year round, deciduous trees usually lack foliage outside the vegetation period. This can reduce their positive air pollution filtration impact during the winter season when PM levels are usually high due to heating (Sgrigna et al., 2015). On the other hand, the litterfall of deciduous species allows a final deposition of PM into the soil and the new leaves allow a renewal of the accumulation area. This becomes especially important in case of the wax embedded PM, which is less likely to be washed off by rain or removed by wind (Przybysz et al., 2014). Although my results show that the amount of PM captured in the wax layer is lower than the amount bound on the surface, the particles bound in the waxy layer have different effects on human health. The smaller fractions ($PM_{0.2}$ and $PM_{2.5}$) are more likely to penetrate the wax layer than the larger fractions (PM_{10} and $PM_{>10}$) and are in parallel the most harmful size classes for human health (Beckett et al., 2000). Despite its relevance, wax-embedded PM are seldomly analysed as it usually takes carcinogenic chloroform to wash of the leaf waxes.

6.3. Limitations and appraisal of results

Although this analysis provides an overview over previous studies and compares amounts of accumulated PM depending on different conditions, there are several shortcomings that should be mentioned.

6.3.1. Limitations regarding methodology

Apart from different conditions and different plant species, the wide range of results could be a consequence of different methods applied for measuring PM amount on foliage. Only measuring the number of particles or the weight of accumulated PM lacks important aspects. Firstly, it does not give information on chemical composition of particles. For the evaluation of the filter performance, this would also be relevant, since it is decisive for health-damaging effects (Cassee et al., 2013). Secondly, ultrafine PM can be taken up by stomata (Grote et al., 2016), but this amount is not integrated in the values. Additionally, when analysing values evaluated by gravimetric methods water-soluble particles are not measured with this approach. Moreover, according to Zhang et al. (2019), 29-46% of PM remains on the leaves when they are cleaned by brush and water.

Also, particle number (N) should be treated with caution, since smaller particles deposited on the leaf surface might merge into bigger particle agglomerates. In that case, particle cover area might be more significant than particle number (Wang et al., 2015).

Most of the leaf samples were taken at a height of about two meters. This could lead to a distortion of values as PM accumulation potential of leaves can vary with height and position in the crown (Hofman et al., 2014). Some trees might form a thicker wax layer on sun exposed leaves in order to protect them against sun and wind. Pollution level on the other hand might be higher on the ground due to traffic (Hofman et al., 2014).

6.3.2. Limitations regarding relevance of results

When considering the roles of trees in tackling air pollution, a punctual measurement of accumulated PM load or particle number per leaf area only provides one partial aspect. For a determination of the extent of air quality improvement by trees, net PM removal is crucial. Results can differ when considering net PM removal, which was shown by Chen et al. (2021). Within his results conifers performed worst. Leaf characteristics such as trichomes and grooves can be helpful in accumulating PM but on the other hand they make it difficult for rain to clean the leaf surface (Chen et al. 2021).

Additionally, it should be mentioned at this point that the effects of a high pollution level on tree physiology are worth considering as well. According to Chaudhary & Rathore (2018) dust deposition can cause alterations of plant functioning, inducing various oxidative stresses and consequently, reduced leaf dry weight. Tree tolerance towards dust varies between tree species (Chaudhary & Rathore, 2018). Plants might react differently to pollution exposure over a long time period. Erosion of waxes was observed e.g., on *Pinus sylvestris* needles, and this can lead to a decrease of PM accumulation (Saebo et al. 2012). This means that the long-term performance and functioning of different tree species can vary over time.

When interpreting data, it has to be contemplated that most of the integrated studies were conducted in urban and periurban regions, especially in China. However, to derive recommendations, further research in various regions is necessary, as leaf traits do not only vary between species but also within species when growing under different environmental conditions.

Finally, when choosing tree species, the knowledge on the efficiency regarding PM accumulation is important but other ecosystem services and disservices have to be taken into consideration as well (Moser et al., 2017). Evergreen species e.g., might be very helpful for mitigating PM pollution in winter but as they keep needles all year round, shading, especially in urban areas might be a problem.

This example shows that the selection of tree species is comprehensive. However, further research is needed to incorporate the filtering function aspect into this complex decision.

7. Conclusion

The filtering potential of trees has so far mainly been determined in China. The high level of pollution and thus high urgency to counteract could be one reason for this. The number of published studies has increased, especially in the last ten years, which illustrates that this research topic is relevant despite a growing awareness about restricting PM pollution by e.g. traffic regulations or usage of particle filters. Most of the studies were conducted *in situ*, measuring weight or number of particles accumulated on foliage. A closer look into the methodologies of the studies, however, renders it obvious that meta-data on the surrounding environmental conditions are often incomplete. In particular, the counter intuitive finding that the highest amount of PM was determined after a maximum of five days without rain illustrates that additional efforts are needed to better comprehend the filter potential of tree species. Above all, a uniform recording and documentation of all abiotic and biotic parameters, which might have an influence on the filter performance, is crucial. This will help to develop a mechanistic understanding on how tree and leaf traits interact with the temporal and spatial highly variable environmental conditions in rural and (peri-)urban environments. As a result, this will allow the selection of the best species according to the site and environmental conditions—safeguarding the capacity of vegetation to provide important environmental services to mankind.

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Sgrigna, G., Sæbø, A., Gawronski, S., Popek, R., & Calfapietra, C. (2015). Particulate Matter deposition on *Quercus ilex* leaves in an industrial city of central Italy. *Environmental Pollution*, *197*, 187–194. https://doi.org/10.1016/j.envpol.2014.11.030

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Xu, X., Yu, X., Mo, L., Xu, Y., Bao, L., & Lun, X. (2019). Atmospheric particulate matter accumulation on trees: A comparison of boles, branches and leaves. *Journal of Cleaner Production*, *226*, 349–356. https://doi.org/10.1016/j.jclepro.2019.04.072

Yan, J., Lin, L., Zhou, W., Ma, K., & Pickett, S. T. A. (2016). A novel approach for quantifying particulate matter distribution on leaf surface by combining SEM and object-based image analysis. *Remote Sensing of Environment*, *173*, 156–161. https://doi.org/10.1016/j.rse.2015.11.033

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Zhang, L., Zhang, Z., Chen, L., & McNulty, S. (2019). An investigation on the leaf accumulation-removal efficiency of atmospheric particulate matter for five urban plant species under different rainfall regimes. *Atmospheric Environment*, *208*, 123–132. https://doi.org/10.1016/j.atmosenv.2019.04.010

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Supplement

Description of methods to study PM accumulation

In order to measure particulate matter, several measurement techniques such as field research, laboratory studies (e.g., wind tunnel experiments) and modelling studies are applied. Studies evaluated in this thesis are mainly field studies using primarily gravimetric and SEM/EDX methods. Most studies focus on foliage and do not measure deposition on branches and boles as the surface area is comparable low (Xu et al., 2019). In the following, a brief overview on the techniques is given, allowing to better judge on the comparability / differences between methodologies.

a) <u>Gravimetric analyses</u>

Gravimetric analyse is the most common method to determine PM load applied by papers integrated in this thesis. Sampling leaves are rinsed with distilled water and in some cases further scrubbed with a brush (He et al., 2019) The eluate is passed through a sieve with a diameter of 100 µm to remove particles larger than 100 µm and afterwards through filters with different pore size. Filters are weighed before and after the filtration process and therefore mass of accumulated PM can be determined. In some cases, leaves are further washed with chloroform in order to dissolve the epicuticular wax layer from the leaf tissue. This allows for determination of the wax-embedded particles. Measurement of leaf surface area allows a calculation of the accumulated PM mass per unit leaf area. In this context, many papers refer to the method applied by Dzierzanowski et al., (2011) (Dzierzanowski et al. 2011; Song et al., 2015). Advantages of gravimetric analyses are time and cost efficiency. However, it has to be taken into account, that the soluble particle matter fraction cannot be quantified as it passes the filters with rinsing water (Corada et al., 2021). Another difficulty is, that ad- and abaxial surface can hardly be measured separately. Further, this method does not evaluate particle number, size distribution and chemical composition of PM.

b) <u>SEM/EDX</u>

Using scanning electron microscopy combined with energy dispersed X-ray spectroscopy (SEM/EDX) allows to study PM size, number and chemical composition of particles without removing them from the leaves (Baldacchini, 2019). With the SEM method a focused electron beam is scanned across the sample. Secondary and backscattered electrons as well as X-rays that result as a signal, are collected by a detector and provide a detailed image (Casuccio et al., 2004). Advantages of this method is that the ad- and abaxial surface of leaves can be analysed separately. Furthermore, images allow not only counting of particles but also an observation of the leaf traits (Sgrigna et al., 2020).

c) Laboratory studies

A common method applied is the wind tunnel method which allows to control wind velocity, pollutant concentration and the diameter of particles. However, due to costs, tunnel size is usually small which limits the sample size. Another difficulty is, that aerosol generator only produces single compounds of uniform size (Yan et al., 2016). Another possibility is that samples are polluted under controlled conditions (e.g. in a glass house) and washed afterwards with water (and chloroform) to measure weight of particles (Łukowski et al., 2020).

d) Modelling studies

Modelling studies mainly estimated PM uptake per forest area but not on an individual tree level. Modelling studies are often based on the i-tree model, that was developed by the United States Forest Service. It combines trees data like number of trees, species, tree height, diameter at breast height and tree cover with local environmental data like hourly meteorological data and air pollution concentration data to estimate hourly pollution removal by trees and shrub (Selmi et al., 2016).

Pace & Grote (2020) for example estimates annual PM removal in g/m^2/year in Berlin, Rome and Munich by using the i-tree model. Schaubroeck et al. (2014) evolved the i-tree model with their CIPAM model which considers different vegetation layers, integrates deposited and resuspended PM during rain events and considers forest change over time.

Supplement Table S1: *List of studies selected for this meta-analysis and their general classification into field or lab experiment, modelling exercise or review. New studies were considered for inclusion until 31.12. 2021*

Nr.	Paper	Methodology
1	Belot, Y., Camus, H., Gauthier, D., & Caput, C. (1994). Uptake of small particles by tree canopies. *Science of The Total Environment*, 157, 1–6. https://doi.org/10.1016/0048-9697(94)90558-4	Lab
2	Łukowski, A., Popek, R., & Karolewski, P. (2020). Particulate matter on foliage of *Betula pendula*, *Quercus robur*, and *Tilia cordata*: Deposition and ecophysiology. *Environmental Science and Pollution Research,* 27(10), 10296–10307. https://doi.org/10.1007/s11356-020-07672-35	Lab
3	Blanusa, T., Fantozzi, F., Monaci, F., & Bargagli, R. (2015). Leaf trapping and retention of particles by holm oak and other common tree species in Mediterranean urban environments. *Urban Forestry & Urban Greening,* 14(4), 1095–1101. https://doi.org/10.1016/j.ufug.2015.10.004	Lab
4	Popek, R., Łukowski, A., & Karolewski, P. (2017). Particulate matter accumulation – further differences between native *Prunus padus* and non-native *P. serotina*. *Dendrobiology,* 78, 85–95. https://doi.org/10.12657/denbio.078.009	Lab
5	Zhang, L., Zhang, Z., Chen, L., & McNulty, S. (2019). An investigation on the leaf accumulation-removal efficiency of atmospheric particulate matter for five urban plant species under different rainfall regimes. *Atmospheric Environment*, 208, 123–132. https://doi.org/10.1016/j.atmosenv.2019.04.010	Lab-Field Combination
6	Mazur J. (2018). Plants as natural anti-dust filters – preliminary research. *Czasopismo Techniczne*, 3. https://doi.org/10.4467/2353737XCT.18.045.8340	Review
7	Pace, R., & Grote, R. (2020). Deposition and resuspension mechanisms into and from tree canopies: A study modelling particle removal of conifer and broadleaves in different cities*. Frontiers in Forests and Global Change*, 3, 26. https://doi.org/10.3389/ffgc.2020.00026	Modelling
8	Przybysz, A., Nersisyan, G., & Gawroński, S. W. (2019). Removal of particulate matter and trace elements from ambient air by urban greenery in the winter season. *Environmental Science and Pollution Research* 26, 473–482. https://doi.org/10.1007/s11356-018-3628-0	Field-experiment
9	Terzaghi, E., Wild, E., Zacchello, G., Cerabolini, B. E. L., Jones, K. C., & Di Guardo, A. (2013). Forest filter effect: Role of leaves in capturing/releasing air particulate matter and its associated PAHs. *Atmospheric Environment*, 74, 378-384. https://doi.org/10.1016/j.atmosenv.2013.04.013.	Field-experiment
10	Sgrigna, G., Sæbø, A., Gawroński, S.W., Popek, R., & Calfapietra, C. (2015). Particulate matter deposition on *Quercus ilex* leaves in an industrial city of central Italy. *Environmental pollution, 197*, 187-194.https://doi.org/10.1016/j.envpol.2014.11.030	Field-experiment
11	Xu, X., Yu, X., Mo, L., Xu, Y., Bao, L., & Lun, X. (2019). Atmospheric particulate matter accumulation on trees: A comparison of boles, branches and leaves. *Journal of Cleaner Production*, 226, 349–356. https://doi.org/10.1016/j.jclepro.2019.04.072	Field-experiment
12	Zhang, W., Wang, B., & Niu, X. (2017). Relationship between leaf surface characteristics and particle capturing capacities of different tree species in Beijing. *Forests*, 8(3), 92. https://doi.org/10.3390/f8030092	Field-experiment
13	Luo, J., Zhou, X., Tian, Y., & Zhang, M. (2018). Research report of particulate matter deposited on leaf surface of major ecological tree species. IOP Conference Series: *Earth and Environmental Science*, 170, 052002. https://doi.org/10.1088/1755-1315/170/5/052002	Field-experiment
14	Popek, R., Gawrońska, H., Wrochna, M., Gawroński, S. W., & Sæbø, A. (2013). Particulate matter on foliage of 13 woody species: Deposition on surfaces and phytostabilisation in waxes – a 3-year study. *International Journal of Phytoremediation*, 15(3), 245–256. https://doi.org/10.1080/15226514.2012.694498	Field-experiment
15	Wang, L., Gong, H., Liao, W., & Wang, Z. (2015). Accumulation of particles on the surface of leaves during leaf expansion. *The Science of the total environment, 532*, 420-34. https://doi.org/10.1016/j.scitotenv.2015.06.014	Field-experiment
16	Leonard, R. J., McArthur, C., & Hochuli, D. F. (2016). Particulate matter deposition on roadside plants and the importance of leaf trait combinations. *Urban Forestry & Urban Greening*, 20, 249–253. https://doi.org/10.1016/j.ufug.2016.09.008	Field-experiment
17	Freer-Smith, P. H., Beckett, K. P., & Taylor, G. (2005). Deposition velocities to *Sorbus aria, Acer campestre, Populus deltoides × trichocarpa* 'Beaupré', *Pinus nigra* and × *Cupressocyparis leylandii* for coarse, fine and ultra-fine particles in the urban environment. *Environmental Pollution*, 133(1), 157–167. https://doi.org/10.1016/j.envpol.2004.03.031	Field-experiment
18	Sæbø, A., Popek, R., Nawrot, B., Hanslin, H. M., Gawronska, H., & Gawronski, S. W. (2012). Plant species differences in particulate matter accumulation on leaf surfaces. *Science of The Total Environment*, 427–428, 347–354. https://doi.org/10.1016/j.scitotenv.2012.03.084	Field-experiment
19	Hofman, J., Wuyts, K., Van Wittenberghe, S., Brackx, M., & Samson, R. (2014). On the link between biomagnetic monitoring and leaf-deposited dust load of urban trees: Relationships and spatial	Field-experiment

	variability of different particle size fractions. *Environmental Pollution*, 189, 63–72. https://doi.org/10.1016/j.envpol.2014.02.020	
20	Dzierżanowski, K., Popek, R., Gawrońska, H., Sæbø, A., & Gawroński, S. W. (2011). Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. *International Journal of Phytoremediation*, 13(10), 1037–1046. https://doi.org/10.1080/15226514.2011.552929	Field-experiment
21	Przybysz, A., Sæbø, A., Hanslin, H. M., & Gawroński, S. W. (2014). Accumulation of particulate matter and trace elements on vegetation as affected by pollution level, rainfall and the passage of time. *Science of The Total Environment*, 481, 360–369. https://doi.org/10.1016/j.scitotenv.2014.02.072	Field-experiment
22	Chen, L., Liu, C., Zou, R., Yang, M., & Zhang, Z. (2016). Experimental examination of effectiveness of vegetation as bio-filter of particulate matters in the urban environment. *Environmental Pollution*, 208, 198–208. https://doi.org/10.1016/j.envpol.2015.09.006	Field-experiment
23	Song, Y., Maher, B. A., Li, F., Wang, X., Sun, X., & Zhang, H. (2015). Particulate matter deposited on leaf of five evergreen species in Beijing, China: Source identification and size distribution. *Atmospheric Environment*, 105, 53–60. https://doi.org/10.1016/j.atmosenv.2015.01.032	Field-experiment
24	He, C., Qiu, K., & Pott, R. (2020). Reduction of urban traffic–related particulate matter—Leaf trait matters. *Environmental Science and Pollution Research*, 27(6), 5825–5844. https://doi.org/10.1007/s11356-019-07160-0	Field-experiment
25	Haynes, A., Popek, R., Boles, M., Paton-Walsh, C., & Robinson, S. A. (2019). Roadside moss turfs in South East Australia capture more particulate matter along an urban gradient than a common native tree species. *Atmosphere*, 10(4), 224. https://doi.org/10.3390/atmos10040229	Field-experiment
26	Kwak, M. J., Lee, J., Kim, H., Park, S., Lim, Y., Kim, J. E., Baek, S. G., Seo, S. M., Kim, K. N., & Woo, S. Y. (2019). The removal efficiencies of several temperate tree species at adsorbing airborne particulate matter in urban forests and roadsides. *Forests*, 10(11), 960. https://doi.org/10.3390/f10110960	Field-experiment
27	Chen, X., Zhou, Z., Teng, M., Wang, P., & Zhou, L. (2015). Accumulation of three different sizes of particulate matter on plant leaf surfaces: Effect on leaf traits. *Archives of Biological Sciences*, 67(4), 1257–1267. https://doi.org/10.2298/ABS150325102C	Field-experiment
28	Liu, J., Cao, Z., Zou, S., Liu, H., Hai, X., Wang, S., Duan, J., Xi, B., Yan, G., Zhang, S., & Jia, Z. (2018). An investigation of the leaf retention capacity, efficiency and mechanism for atmospheric particulate matter of five greening tree species in Beijing, China. *Science of the Total Environment*, 616–617, 417-426. https://doi.org/10.1016/j.scitotenv.2017.10.314	Field-experiment
29	Baldacchini, C., Sgrigna, G., Clarke, W., Tallis, M., & Calfapietra, C. (2019). An ultra-spatially resolved method to quali-quantitative monitor particulate matter in urban environment. *Environmental Science and Pollution Research*, 26(18), 18719–18729. https://doi.org/10.1007/s11356-019-05160-8	Field-experiment
30	Beckett, K. P., Freer-Smith, P. H., & Taylor, G. (2000). The capture of particle pollution by trees at five contrasting urban sites. *Arboricultural Journal*, 24(2–3), 209–230. https://doi.org/10.1080/03071375.2000.9747288	Field-experiment
31	Mori, J., Hanslin, H. M., Burchi, G., & Sæbø, A. (2015). Particulate matter and element accumulation on coniferous trees at different distances from a highway. *Urban Forestry & Urban Greening*, 14(1), 170–177. https://doi.org/10.1016/j.ufug.2014.09.005	Field-experiment
32	Popek, R., Przybysz, A., Gawrońska, H., Klamkowski, K., & Gawroński, S. W. (2018). Impact of particulate matter accumulation on the photosynthetic apparatus of roadside woody plants growing in the urban conditions. *Ecotoxicology and Environmental Safety*, 163, 56–62. https://doi.org/10.1016/j.ecoenv.2018.07.068	Field-experiment
33	Mo, L., Ma, Z., Xu, Y., Sun, F., Lun, X., Liu, X., Chen, J., & Yu, X. (2015). Assessing the capacity of plant species to accumulate particulate matter in Beijing, China. *PLOS ONE*, 10 (10).. https://doi.org/10.1371/journal.pone.0140664	Field-experiment
34	Shao, F., Wang, L., Sun, F., Li, G., Yu, L., Wang, Y., Zeng, X., Yan, H., Dong, L., & Bao, Z. (2019). Study on different particulate matter retention capacities of the leaf surfaces of eight common garden plants in Hangzhou, China. *The Science of the total environment*, 652, 939-951 . https://doi.org/10.1016/j.scitotenv.2018.10.182	Field-experiment
35	Shi, J., Zhang, G., An, H., Yin, W., & Xia, X. (2017). Quantifying the particulate matter accumulation on leaf surfaces of urban plants in Beijing, China. *Atmospheric Pollution Research*, 8(5), 836–842. https://doi.org/10.1016/j.apr.2017.01.011	Field-experiment
36	Chen, L., Liu, C., Zhang, L., Zou, R., & Zhang, Z. (2017). Variation in tree species ability to capture and retain airborne fine particulate matter (PM2.5). *Scientific Reports*, 7(1), 3206. https://doi.org/10.1038/s41598-017-03360-44	Field-experiment
37	Beckett, K. P., Freer-Smith, P., & Taylor, G. (2000). Effective tree species for local air quality management. *Journal of Arboriculture*. 26.	Field-experiment
38	He, C., Qiu, K., Alahmad, A., & Pott, R. (2020). Particulate matter capturing capacity of roadside evergreen vegetation during the winter season. *Urban Forestry & Urban Greening*, 48, 126510. https://doi.org/10.1016/j.ufug.2019.126519	Field-experiment

39	Thao, N.T., Yu, X., & Zhang, H. (2014). Deposition of particulate matter of different size fractions on leaf surfaces and in epicuticular waxes of urban forest species in summer and fall in Beijing, China. *International Journal of Sciences*, 3, 12-22.	Field-experiment
40	Wang, H., Shi, H., & Wang, Y. (2015). Effects of weather, time, and pollution level on the amount of particulate matter deposited on leaves of *Ligustrum lucidum*. *The Scientific World Journal*, 2015, 1–8. https://doi.org/10.1155/2015/935956	Field-experiment
41	Li, Y., Wang, S., & Chen, Q. (2019). Potential of thirteen urban greening plants to capture particulate matter on leaf surfaces across three levels of ambient atmospheric pollution*. International Journal of Environmental Research and Public Health*, 16(3), 402. https://doi.org/10.3390/ijerph16030402	Field-experiment
42	Popek, R., Gawrońska, H., & Gawroński, S. W. (2015). The level of particulate matter on foliage depends on the distance from the source of emission. *International Journal of Phytoremediation*, 17(12), 1262–1268. https://doi.org/10.1080/15226514.2014.989339	Field-experiment
43	Xu, Y., Xu, W., Mo, L., Heal, M. R., Xu, X., & Yu, X. (2018). Quantifying particulate matter accumulated on leaves by 17 species of urban trees in Beijing, China. *Environmental Science and Pollution Research*, 25(13), 12545–12556. https://doi.org/10.1007/s11356-018-1478-29	Field-experiment
44	Liu, J., Zhang, R., Liu, H., Duan, J., Kang, J., Guo, Z., Xi, B., & Cao, Z. (2018). Assessing the particulate matter removal abilities of tree leaves. *Journal of Visualized Experiments*, 140, 58026. https://doi.org/10.3791/58026	Field-experiment
45	Prusty, B. A. K., Mishra, P. C., & Azeez, P. A. (2005). Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. *Ecotoxicology and Environmental Safety*, 60(2), 228–235. https://doi.org/10.1016/j.ecoenv.2003.12.021	Field-experiment
46	Shi, S., Wu, Z., Liu, F., & Fan, W. (2016). Retention of atmospheric particles by local plant leaves in the Mount Wutai scenic area, China. *Atmosphere*, 7(8), 104. https://doi.org/10.3390/atmos7080106	Field-experiment
47	Singh, S., Bhattacharya, P., & Gupta, N. C. (2018). Dust particles characterization and innate resistance for *Thevetia peruviana* in different land-use pattern of urban area. *International Journal of Environmental Science and Technology,* 15(5), 1061–1072. https://doi.org/10.1007/s13762-017-1461-5	Field-experiment
48	Sgrigna, G., Baldacchini, C., Dreveck, S., Cheng, Z., & Calfapietra, C. (2020). Relationships between air particulate matter capture efficiency and leaf traits in twelve tree species from an Italian urban-industrial environment. *Science of The Total Environment*, 718, 137310. https://doi.org/10.1016/j.scitotenv.2020.137333	Field-experiment
49	Dzierżanowski, K., & Gawroński, S. W. (2011). Use of trees for reducing particulate matter pollution in air. *Challenges of Modern Technology*, 2(1), 69–73.	Field-experiment
50	Wang, H., Shi, H., Li, Y., Yu, Y., & Zhang, J. (2013). Seasonal variations in leaf capturing of particulate matter, surface wettability and micromorphology in urban tree species. *Frontiers of Environmental Science & Engineering,* 7(4), 579–588. https://doi.org/10.1007/s11783-013-0524-1	Field-experiment
51	Zha, Y., Shi, Y., Tang, J., Liu, X., Feng, C., & Zhang, Y. (2018). Spatial-temporal variability and dust-capture capability of 8 plants in urban China. *Polish Journal of Environmental Studies*, 28(1), 453–462. https://doi.org/10.15244/pjoes/81686	Field-experiment
52	Hatami-manesh, M., Mortazavi, S., Solgi, E., & Mohtadi, A. (2021). Assessing the uptake and accumulation of heavy metals and particulate matter from ambient air by some tree species in Isfahan Metropolis, Iran. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-021-13524-2	Field-experiment
53	Jia, M., Zhou, D., Lu, S., & Yu, J. (2021). Assessment of foliar dust particle retention and toxic metal accumulation ability of fifteen roadside tree species: Relationship and mechanism. *Atmospheric Pollution Research*, 12(1), 36–45. https://doi.org/10.1016/j.apr.2020.08.041	Field-experiment
54	Popek, R., Haynes, A., Przybysz, A., & Robinson, S. A. (2019). How much does weather matter? Effects of rain and wind on PM accumulation by four species of Australian native trees. *Atmosphere*, 10(10), 633. https://doi.org/10.3390/atmos10100633	Field-experiment
55	Jin, E. J., Yoon, J. H., Bae, E. J., Jeong, B. R., Yong, S. H., & Choi, M. S. (2021). Particulate matter removal ability of ten evergreen trees planted in Korea urban greening. *Forests,* 12(4), 438. https://doi.org/10.3390/f12040457	Field-experiment
56	Chen, G., Lin, L., Hu, Y., Zhang, Y., & Ma, K. (2021). Net particulate matter removal ability and efficiency of ten plant species in Beijing. *Urban Forestry & Urban Greening*, 63, 127230. https://doi.org/10.1016/j.ufug.2021.127230	Field-experiment
57	Popek, R., Łukowski, A., Bates, C., & Oleksyn, J. (2017). Accumulation of particulate matter, heavy metals, and polycyclic aromatic hydrocarbons on the leaves of *Tilia cordata* Mill. In five Polish cities with different levels of air pollution. *International Journal of Phytoremediation*, 19(12), 1134–1141. https://doi.org/10.1080/15226514.2017.1328413	Field-experiment

Supplement Table S2: *Summary of statistical analyses on effect of pollution level on PM load in µg cm⁻²*

µg cm⁻²		Min	1st Quantile	Median	Mean	3rd Quantile	Max
$PM_{0.2}$	high [b]	1	2	2	2.76	3	9
	medium	-	-	-	-	-	-
-	low [a]	5	1	1	1.47	2	4
$PM_{2.5}$	high [b]	0.42	2.73	4	4.82	6	25
	medium [b]	0.1	2	2.3	4.08	6	14
	low [a]	0.43	1	2	3.3	3	73
PM_{10}	high [b]	3	8.16	12	15.28	18.82	58
	medium [a]	0.1	2	3.77	11.8	14	50
	low [a]	0.75	1.89	6	6.85	10	27
$PM_{>10}$	high [b]	15	35	115	160.8	277.5	380
	medium [a]	0.5	4	23	28.28	44.3	114.6
	low [a]	1.25	3.61	5.51	7.78	6.95	50

Supplement Table S3: *Summary of statistical analyses on effects of sampling site on PM load in µg cm⁻²*

µg cm⁻²		Min	1st Quantile	Median	Mean	3rd Quantile	Max
$PM_{0.2}$	rural [b]	0.5	1	1	1.47	2	4
	periurban [c]	1	2	3	3.83	5	15
	urban [a]	0.15	0.22	0.33	0.38	0.55	0.67
$PM_{2.5}$	rural [a]	0.43	1	2	3.3	3	73
	periurban [c]	0.1	2	3	4.89	6	25
	urban [b]	0.01	1.15	2.8	11.28	6	300
PM_{10}	rural [a]	0.75	1.89	6	6.85	10	27
	periurban [b]	0.1	3	8	12.69	16	99.3
	urban [ab]	0.06	3	6.94	18.612	15.05	340
$PM_{>10}$	rural [a]	1.25	3.61	5.510	7.79	6.95	50
	periurban [b]	0.50	4.00	13.72	31.46	30	380
	urban [c]	1.62	9.72	17	30.37	35.5	178.51

Supplement Table S4: *Summary of statistical analyses on effect of sampling site on particle number in N mm⁻²*

N mm⁻²		Min	1st Quantile	Median	Mean	3rd Quantile	Max
$PM_{0.2}$	rural	-	-	-	-	-	-
	periurban [a]	1844	1886	2170	2349	2633	3211
	urban [b]	2000	3100	10500	13395	23000	32000
$PM_{2.5}$	rural	-	-	-	-	-	-
	periurban [a]	458	960.8	1480.5	1544.5	2019	3264
	urban [b]	800	1625	8500	36742	13000	318700
PM_{10}	rural	-	-	-	-	-	-
	periurban [a]	1	8.5	19	58	61.75	299
	urban [b]	388	825	2750	4435	7950	16100
$PM_{>10}$	rural	-	-	-	-	-	-
	periurban [a]	0	2.25	4.50	4	5	11
	urban [b]	90	250	400	1201	2000	3000

Supplement Table S5: *Summary of statistical analyses on effect of days without rain before sampling on PM load in µg cm⁻²*

µg cm⁻²		Min	1st Quantile	Median	Mean	3rd Quantile	Max
$PM_{0.2}$	≤5	-	-	-	-	-	-
	6-15	-	-	-	-	-	-
	≥16	0.15	0.22	0.33	0.38	0.55	0.67
$PM_{2.5}$	≤5 [b]	0.50	3.3	30	49.09	41	30
	6-15[a]	0.1	1.42	2	3.51	4	21
	≥16[a]	0.33	0.89	1.83	4.99	3.36	48
PM_{10}	≤5[c]	0.9	5	30	59.34	50	340
	6-15[a]	0.1	2	3.9	7.78	8.76	52
	≥16[b]	0.89	3.36	7.85	13.2	21.76	57
$PM_{>10}$	≤5[b]	1.62	23.36	46.36	53.57	69.4	152
	6-15[a]	0.5	5	14.87	20.87	27.76	102
	≥16[ab]	4	13.5	24.5	44.53	56.27	178.51

Supplement Table S6: *Summary of statistical analyses on effect of category of tree on PM load in µg cm^{-2}*

µg cm^{-2}		Min	1st Quantile	Median	Mean	3rd Quantile	Max
$PM_{0.2}$	Deciduous broadleaves [a]	0.15	1	2	2.68	3	18.5
	Deciduous conifers	---	---	---	---	---	---
	Evergreen broadleaves [a]	0.65	1	2	1.73	2	3
	Evergreen Conifers b	0.47	4	5	5.83	8	15
$PM_{2.5}$	Deciduous broadleaves [a]	0.01	1.33	2.69	6.86	5.53	230
	Deciduous conifers [ab]	1	2	3	7.9	3.5	30
	Evergreen broadleaves [b]	0.01	2.4	4.17	5.76	8	41
	Evergreen Conifers b	0.01	2.97	5	20.87	14.5	300
PM_{10}	Deciduous broadleaves [a]	0.1	2.74	7	13.22	13	340
	Deciduous conifers [ab]	0.1	0.55	1	11.03	16.5	32
	Evergreen broadleaves [a]	0.06	3.87	10.64	15.85	24.88	41
	Evergreen Conifers [b]	1	8	17	34.97	38	340
$PM_{<10}$	Deciduous broadleaves [a]	0.5	5.68	12.20	22.23	27.76	152
	Deciduous conifers [ab]	3	14.25	25.5	25.5	36.75	48
	Evergreen broadleaves [b]	6.35	10.64	40.00	33.55	45	148.74
	Evergreen Conifers [b]	5	22.88	42.66	69.48	81.25	380

Supplement Table S7: *Summary of statistical analyses on effect of category of tree on particle number in N mm^{-2}*

N mm^{-2}		Min	1st Quantile	Median	Mean	3rd Quantile	Max
$PM_{0.2}$	Deciduous broadleaves [b]	2000	3100	10500	13395	23000	32000
	Deciduous conifers	-	-	-	-	-	-
	Evergreen broadleaves [a]	1844	1886	2170	2349	2633	3211
	Evergreen Conifers	-	-	-	-	-	-
$PM_{2.5}$	Deciduous broadleaves [b]	657	2000	13000	77086	125000	440000
	Deciduous conifers	-	-	-	-	-	-
	Evergreen broadleaves [a]	458	1056	1677	8232	2208	87400
	Evergreen Conifers [b]	2009	5876	100400	123037	214200	318700
PM_{10}	Deciduous broadleaves [b]	187	1000	4200	5269	7925	18000
	Deciduous conifers	-	-	-	-	-	-
	Evergreen broadleaves [a]	1	8	17	140	61	1500
	Evergreen Conifers [b]	388	631	4900	5593	8250	16100
$PM_{>10}$	Deciduous broadleaves [b]	200	250	500	1066	2000	3000
	Deciduous conifers	-	-	-	-	-	-
	Evergreen broadleaves [a]	0	3	5	29	5	330
	Evergreen Conifers [ab]	90	180	225	465	510	1320