Trait-mediated leaf retention of atmospheric particulate matter in fourteen tree species in southern China

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Research Article

Abstract

Particulate air pollution is a serious threat to human health, especially in urban areas, and trees can act as biological filters and improve air quality. However, studies on greening tree species selection are rare. We measured three particular matter adsorption metrics ($PM_{2.5}$, $PM_{2.5-10}$ and $PM_{>10}$ captured per leaf area) and six functional traits for each of fourteen species and estimated their minimum light requirements based on field surveys. We found that shade-tolerant species captured more coarse particles ($PM_{2.5-10}$) than light-demanding species. For traits, a strong negative correlation was found between photosynthetic capacity and adsorption capacity for all three PM size fractions, indicating that in comparison to acquisitive species, conservative species captured larger amounts of particles. Moreover, denser wood species and smaller leaves were more efficient in capturing large particles ($PM_{>10}$), while species with 'expensive' leaves (high leaf N or P) were more efficient in capturing fine particles ($PM_{2.5}$), indicating that capturing large and fine particles was related to mechanical stability traits and leaf surface traits, respectively. Our results demonstrated that the metabolism (e.g., photosynthetic capacity) and chemistry (e.g., leaf N and leaf P) of leaves help explain species capacity to capture PM. We encourage future studies to investigate the ecosystem functions and stress tolerance of tree species with the same framework and trait-based methods.

Introduction

Developing countries such as China have experienced fundamental changes in recent decades, while gains in wealth have been achieved at a severe cost to the environment (Liu et al. 2018; Xu et al. 2018). Air pollution is a major threat to people's health, particularly in urban areas (Przybysz et al. 2014; Yan et al. 2016), due to particulate matter (PM) emissions linked to traffic and industry (Simon et al. 2016). Coarse particles can cause lung diseases, while smaller particles, such as $PM_{2.5}$, can be inhaled more deeply into the lungs (Beckett et al. 2000; Liang et al. 2016) and have been widely recognized as more harmful to human health. Air pollution is estimated to contribute to at least five million premature deaths each year (WHO 2014).

Vegetation can reduce particle concentrations and thereby improve air quality (Litschke and Kuttler 2008; Liu et al. 2013; Shi et al. 2017; Weerakkody et al. 2018a). A leaf is the main organ for particle deposition (Weerakkody et al. 2018b) and can even biodegrade or transform pollutants into less or nontoxic molecules with its habituated microbes and endophytes (Zhang et al. 2017). Recognizing what kind of plants are more powerful in capturing airborne PM is important but challenging because the retention capacity of leaves in terms of accumulating PM is influenced by a variety of factors, such as the concentration of atmospheric PM (Luo et al. 2020), days after rainfall (Xu et al. 2020), wind speed (Beckett et al. 2000), leaf stage (Nguyen et al. 2015) and sampling season (Zhang et al. 2017), which are linked with surface moisture (Wang et al. 2013; Sun et al. 2020). Therefore, it is necessary to investigate what kind of trait could improve species' PM adsorption abilities (Janhäll 2015; Shao et al. 2019). For example, species with smaller leaves, more complex leaf structure, waxy leaves and hairier leaves usually capture PM more efficiently (Beckett et al. 2000; Dzierżanowski et al. 2011; Weerakkody et al. 2017; Sun et al. 2018; Liu et al. 2019). These findings have important significance for selecting greening tree species, which is the primary task in the construction of urban forests.

In comparison to ecosystem functions, environmental stress tolerance is sometimes even more important in greening tree species selection (Chaudhary and Rathore 2018, 2019; Przybysz et al. 2021). However, there are very few studies investigating species' PM adsorption abilities in relation to species' environmental stress tolerance, such as shade tolerance and drought tolerance. Therefore, it is of great importance to test whether species with high PM adsorption abilities are fast- or slow-growing species and whether they are resource-demanding species. Because

light is the major limiting resource in moist forests (Zhao and He 2016), we specifically sought to determine how PM adsorption abilities are correlated with the light requirements of tree species (Question 1).

Theoretically, plant traits can track environmental changes and reflect the adaptive strategies of plants (Liu et al. 2021). Dust accumulation reduces the light availability of leaves (Zhu et al. 2019) and may inhibit chlorophyll biosynthesis (Chen et al. 2015) and stomatal conductance (Lewis et al. 2017), which is important for plant photosynthesis (Hetherington and Woodward 2003; Yu et al. 2018). Consequently, species with a greater ability to accumulate PM might need to be more shade tolerant from the perspective of evolution. We therefore hypothesized that species with high PM accumulation abilities should be able to adapt to poor light environments (Hypothesis 1).

In forest ecology, there is a well-established trade-off between the survival rate in deep shade and the growth rate in bright light (Adler et al. 2014). Fast-growing species that rapidly acquire resources thrive in rich light environments, while slow-growing species that conserve resources are dominant in poor light environments (Lohbeck et al. 2013). This acquisitive-conservative trade-off points to the extremes of a continuum in plant design, and the position of a species along this continuum can be quantified by its functional traits (Poorter et al. 2008; Wright et al. 2010). For instance, an acquisitive species tends to have a high photosynthetic capacity, dark respiration rate, specific leaf area (SLA) and leaf nitrogen content (LNC) and hence a high growth rate. In contrast, conservative species tend to have thicker leaves and a higher wood density (WD), reducing the volumetric stem growth rate but facilitating leaf and stem protection and high survival rates (Chave et al. 2009). In this study, we tested whether species with high PM adsorption abilities are characterized by conservative or acquisitive functional traits (Question 2).

Conservative species commonly have high WD and leaf thickness but a low SLA and photosynthetic capacity, suggesting a low growth rate strategy (Firn et al. 2019). Low growth rate species tend to produce durable leaves with long life spans (Adler et al. 2014). The tough leaves of these species may be associated with complex leaf surface structure and waxes, which could trap PM (Dzierżanowski et al. 2011). Therefore, we hypothesized that species with high PM accumulation capacities should be characterized by conservative traits (Hypothesis 2).

If these two hypotheses were confirmed, then we would test the third question relating to which traits are good predictors of the PM accumulation capacities of species (Question 3). The functional traits measured in this study, including photosynthetic capacity, leaf length, SLA, WD, LNC and leaf phosphorus content (LPC), represent relatively easily measured characteristics that can be obtained for large numbers of species (Li et al. 2021). Relationships among functional traits and PM adsorption capacities may reflect direct effects but could also result from trait coevolution (Reich et al. 2003). Therefore, we used structural equation modelling (SEM) to investigate the relationships among a suite of traits and PM adsorption capacities of different size fractions.

To test the first two hypotheses and establish linkages between plant functional traits and ecosystem functioning (PM adsorption in this study), we sampled leaves from fourteen evergreen tree species (Fig. 1) and experimentally measured their PM adsorption capacities. We then quantified shade tolerance and measured six functional traits of these species and compared them with their PM adsorption abilities.

Methods

Study site

The study was conducted in a 50-ha dynamic forest plot in the Heishiding Provincial Nature Reserve (23°27'N, 111°52'E; altitude, 150–927 m), located in Guangdong Province, southern China. This region is covered by a

subtropical evergreen broad-leaved forest and has a subtropical moist monsoon climate. The annual precipitation is approximately 1700 mm, and the mean daily temperature is 19.6°C.

Quantitative assessment of PM capturing ability

Samples were collected from three individuals for each of the fourteen species. For each individual, 10–50 fully expanded mature leaves were collected at 2–5 metre above-ground with a high branch scissor. Samples from the same tree were then put in a plastic bag, sprinkled water, transported to the laboratory and stored in a refrigerator at 4°C until the laboratory experiment.

To ensure that all samples experienced similar dust conditions, we used a dust box, a dust grinder and an air blower (Fig. 2) to simulate a busy road environment, an approach similar to deposition chamber experiments (Hwang et al. 2011) or wind tunnel experiments (Burkhardt et al. 1995sänen et al. 2013; Zhang et al. 2017). First, we cleaned the samples by immersing them with 250 ml distilled water and washed them with a no-hair-loss brush. Next, the cleaned leaves were hung on a rope installed in an experimental box (1.4 m × 1.2 m × 0.8 m, Fig. 2). Sixty grams of soil was ground to powder, sieved and blown into the box to simulate a cloud of dust and left to set for half an hour. We then removed the dusted leaves and measured the PM retained on them.

The method for rinsing and weighing was similar to that described by Dzierżanowski et al. (2011). The filters and small beakers were dried for 60 minutes at 80°C in a drying oven and then left in the weighing room for an hour to stabilize the humidity and obtain a constant weight (W_1). We immersed leaves with distilled water, cleaned them softly with a nylon brush and then washed them with distilled water. In the next step, the rinse water was filtered sequentially using 10 μm and 2.5 μm filters (Whatman, UK, Types 91 and 42, respectively), and the eluent was poured into small beakers. The filters and beakers were oven dried at 80°C for 8 hours and 12 hours, respectively, and then left in the weighing room for an hour to obtain constant humidity and weight (W_2). Leaf areas (S) of the samples were measured using an Epson Expression 11000XL scanner (Epson, Inc., USA) and calculated using the Photoshop CC2019 software (Adobe Corp., USA). The amount of PM was expressed per unit area (cm^2) of one side of the leaf surface and calculated as (W_2-W_1)/S.

Shade tolerance estimation

The 50-ha plot (1000 m × 500 m) was established following the ForestGEO (https://www.forestgeo.si.edu) protocol in 2011, and all free-standing individuals with diameters at breast height greater than 1 cm were tagged, mapped, measured and identified to species. More than 270000 stems belonging to 245 species were recorded in the first census. The understorey light availability was estimated using hemispherical photography at 2352 locations randomly distributed within the 50-ha plot (Zhao and He 2016), and light availability was then interpolated to grids of 10 m × 10 m using ordinary kriging in the AUTOMAP package (Hiemstra et al. 2009) to estimate the environmental conditions where the individuals were located. The minimum light requirements (shade tolerance) of the species were estimated by calculating the 10th percentile of the distribution of juveniles (height < 4 m) in relation to light availability. There were at least 200 juveniles for each of the 14 species in the 50-ha plot.

Functional trait measurements

We measured six traits, including leaf length (LL), maximum rate of electron transport (J_m), specific leaf area (SLA), wood density (WD), leaf nitrogen concentration (LNC) and leaf phosphorus concentration (LPC). Leaf length was averaged from the samples collected for PM accumulation measurements. However, the other five traits were measured separately at other times on different sampled individuals.

J_m represents the light saturated photosynthetic capacity per leaf area (Rascher et al. 2000). For J_m measurements, a total of 1056 leaves from 335 individuals of the 14 species were sampled. Details on the samplings and measurements can be found in our previous study (Feng et al. 2018). SLA, WD, LNC and LPC were measured in a total of 464 individuals of the fourteen species. Details on these samplings and measurements can also be found in our previous studies (Chen Y. 2015; He et al. 2018; Li et al. 2021). Shade-tolerant species with durable leaves tend to have lower J_m, higher WD and lower SLA than those of light-demanding species with high leaf turnover rates (Walters and Reich 1999; Reich 2014).

Statistical analysis

One-way analysis of variance (ANOVA) was applied to test whether individual PM values differed among species. If the difference among the species was significant, then the significance of the differences between the mean values was tested using Tukey's honest significant difference test (HSD) at $\alpha = 0.05$ with the function "HSD.test" in the R package "agricolae" (R Development Core Team 2016).

To test the relationship between shade tolerance and PM accumulation capacities, we examined the response of PM to minimum light requirements using simple linear regressions. To test the effect of functional traits on PM accumulation capacities, we also examined the response of PM to traits using simple linear regressions. To better meet the assumptions of normality and homogenous variances, PM, shade tolerance and trait values, except for WD, were log transformed before analysis.

Because functional traits are correlated with each other, bivariate relationships alone provide limited information. We used a structural equation model with the function "psem" in the R package "piecewiseSEM". Initially, all possible paths were allowed in the model, and the complex model was further simplified by removing nonsignificant paths. This approach is useful for exploring the comparative strength of relationships. A bidirectional line was used to denote the equivalent models.

Results

Among the 14 species studied, accumulated total suspended particles (TSP) per leaf area ranged from 1.46 $g \cdot m^{-2}$ to 4.11 $g \cdot m^{-2}$, $PM_{2.5}$ ranged from 0.17 $g \cdot m^{-2}$ to 0.82 $g \cdot m^{-2}$, $PM_{2.5-10}$ ranged from 0.12 $g \cdot m^{-2}$ to 1.29 $g \cdot m^{-2}$, and $PM_{>10}$ ranged from 0.97 $g \cdot m^{-2}$ to 2.44 $g \cdot m^{-2}$ (Fig. 3 and Table 1). According to one-way ANOVA, there were significant differences in $PM_{2.5}$, $PM_{2.5-10}$ and TSP capturing abilities ($P < 0.05$) among the species, whereas there were no significant differences in $PM_{>10}$ capturing abilities among the species ($P = 0.06$).

Relationships between shade tolerance and PM accumulation capacities

We found that all three PM accumulation metrics were negatively correlated with the minimum light requirements (shade tolerance) of the species, but only the relationship between $PM_{2.5-10}$ and shade tolerance was significant ($R^2 = 0.72$, P < 0.001, Fig. 4).

Bivariate relationships between functional traits and PM accumulation capacities

For the morphological traits, we found that $PM_{2.5-10}$ and $PM_{>10}$ accumulation capacities were negatively correlated with leaf length (Fig. 5b, c), whereas nonsignificant correlations were observed between $PM_{2.5}$ accumulation capacity and leaf length (Fig. 5a). For the metabolism traits, photosynthetic capacity (J_m) was negatively correlated with PM accumulation capacity for all particle size fractions (Fig. 5d-f).

For the economic traits, the relationships between specific leaf area (SLA) and $PM_{2.5}$, $PM_{2.5-10}$ and $PM_{>10}$ accumulation capacities were nonsignificant (Fig. 6a-c). Wood density (WD) was positively correlated with $PM_{>10}$ accumulation capacity (Fig. 6f), whereas it was not significantly correlated with $PM_{2.5}$ and $PM_{2.5-10}$ accumulation capacities (Fig. 6d, e).

For the leaf chemical traits, leaf nitrogen content (LNC) was positively correlated with $PM_{2.5}$ (Fig. 7a), whereas it was nonsignificantly correlated with $PM_{2.5-10}$ and $PM_{>10}$ accumulation capacities (Fig. 7b-c). Similar patterns were found for leaf phosphorus content (LPC), where $PM_{2.5}$ accumulation capacity was positively correlated with LPC (Fig. 7d), and the relationships between $PM_{2.5-10}$ and $PM_{>10}$ and LPC were nonsignificant (Fig. 7e, f).

Path analysis

Among the six traits LNC, LPC, SLA, WD, leaf length and J_m, mainly J_m, leaf length and LPC influenced PM accumulation capacities. Leaf length decreased the $PM_{>10}$ accumulation capacity and LPC increased the fine particle ($PM_{2.5}$) accumulation capacity. The photosynthetic capacities of leaves (J_m), which may be related to cuticle thinness, decreased the PM retention capacities of all three size classes (Fig. 8).

Discussion

Leaf characteristics, including both leaf architecture and material composition, may influence the ability of a leaf surface to accumulate PM (Liang et al. 2016). In the present study, we found that suites of functional traits displayed a tight association the PM accumulation capacity of leaf area for each species. We showed that species with a small leaf size (low LL), low photosynthetic capacity (low J_m), high input into construction (high WD) and a conservative nutrient use strategy (high LNC and LPC) increased in PM accumulation capacities. Our results indicate that conservative species (characterized by low J_m and high WD) may have higher PM accumulation capacities than acquisitive species (characterized by high J_m and low WD) and that species with high PM accumulation capacities are adapted to poor light environments.

Leaf size affected PM retention capacity.

We found that smaller leaves captured more PM per unit leaf area than larger leaves, especially for coarse and large particles (Fig. 5a-c). In line with our results, Weerakkody et al. (2018b) found that smaller synthetic leaves accumulate more PM than larger synthetic leaves with the same surface characteristics. This correlation between leaf size and PM accumulation capacity was also supported by field surveys (Leonard et al. 2016) but not by the results of some other studies (Sæbø et al. 2012). Scanning electron microscopy images have shown that more particles are distributed near leaf edges (Weerakkody et al. 2018b); therefore, in comparison to broadleaved species, conifer species commonly capture larger amounts of particles (Freer-Smith et al. 2005; Liu et al. 2012).

However, broadleaved species have been reported to have higher leaf retained PM wash-off efficiency than conifer species (Luo et al. 2020), and PM wash-off events are important for the net removal of airborne PM (Xu et al. 2020).

Shade-tolerant species captured larger amounts of PM per area than light-demanding species

The stress tolerances of species (e.g., drought tolerance or shade tolerance) are sometimes even more important than the functions of species when we design vegetation barriers for air pollution abatement (Barwise and Kumar 2020). Species must adapt to the shade conditions created by the deposited dust on leaves, tall buildings and other vegetation. In comparison to light-demanding species, shade-tolerant species have been shown to better survive under shaded conditions, but they have lower maximum photosynthetic rates under high light conditions (Valladares and Niinemets 2008). We found a significantly negative correlation between minimum light requirements and $PM_{2.5-10}$ retention capacities for the species. Moreover, light-demanding species usually have higher photosynthetic capacities than shade-tolerant species. Therefore, the finding that photosynthetic capacity (J_m) was significantly negatively correlated with the PM retention capacity of the species for all particle size classes (Fig. 5d-f) confirmed that species with high PM accumulation abilities are adapted to poor light environments. In this study, we showed that J_m is a good predictor and that it alone predicted 45−64% (for different PM size classes) of interspecific variation in PM accumulation. Compared with other commonly used traits, such as hairiness, roughness and waxiness of the leaf surface, photosynthetic capacity (J_m) is objective and easily measured.

Relationships between economic traits and PM accumulation capacities

For leaf economics, an axis exists from 'cheap' tissue investment and fast returns to 'expensive' tissue investment and slow returns (Wright et al. 2004). Species with 'expensive' economic traits, such as low specific leaf area (SLA), tend to have a long leaf lifespan and low relative growth rates but high survival rates (Adler et al. 2014). These species produce durable leaves with thick cuticles (Kitajima 1994) where interactions between PM and leaves occur. We thereby expected that 'expensive' leaves should have high PM accumulation capacities, and a negative relationship between SLA and PM deposition rate had been reported by a previous wind-tunnel experiment (Chiam et al. 2019). Unexpectedly, nonsignificant correlations were found between SLA and all three PM size fractions in this study (Figs. 6a-c and 8). This result probably occurred because we used the species mean SLA value to characterize all individuals of a species. However, intraspecific SLA variation can arise from both phenotypic plasticity and genetic diversity (Siefert et al. 2015).

We found that species with denser wood accumulated larger amounts of large particles ($PM_{>10}$, Fig. 4f). Species with high wood density (WD) represent a 'slow' life history strategy (Wright et al. 2010); i.e., they have a limited potential growth rate but have low mortality risk under shaded conditions. A negative relationship between WD and leaf size was found in this study (Fig. 6) and has also been reported in some previous studies (Wright et al. 2007). This scenario occurs probably because species with denser wood usually have lower hydraulic conductivity and thereby cannot support large leaves as species with soft wood (Chave et al. 2009). Wet leaves more easily retain PM; however, denser wood species with lower hydraulic conductivity were found to have higher PM accumulation capacity (Fig. 6f). The correlations between WD and $PM_{>10}$, as the path analysis demonstrated (Fig. 8), were the result of a complex correlation network in the trait space.

We found that leaf N and P concentrations were both positively correlated with $PM_{2.5}$ accumulation capacities (Fig. 7a, d). N and P are the two most limiting elements to plants and have specific functions in leaves. N is important for enzymatic activity, and P affects protein synthesis. Greater leaf N and P concentrations may enhance metabolic activity and facilitate the formation of complex leaf surface structures.

Except for thicker cuticles for adsorbing PM, trees with 'expensive' leaves (low SLA) and denser wood may have higher structural stability (Reich et al. 1991) and sway less in wind, which may reduce the resuspension of PM back into the air (Chiam et al. 2019) and further improve their PM capturing efficiencies.

Accumulation of different size fractions of PM

PM of different sizes has varying effects on human health (Przybysz et al. 2014), with the smallest fraction considered to be the most hazardous. Particles > 100 μm in diameter have not been measured in many studies (Przybysz et al. 2014; Xu et al. 2017; Cai et al. 2017). However, large particles near busy urban roads are not harmless, especially when they contain large amounts of heavy metals such as mercury and lead (Liu et al. 2012). We did not exclude $PM_{>100}$ in the washing solutions, but the ground soils used in this experiment were sieved through a metal sieve (retention 300 μm) before being blown into the experimental box. Large particles ($PM_{>10}$) made up the greatest mass proportion (48.9–75.3%) of total suspended particles, followed by the coarse fraction (7.8–35.6%) and then the fine fraction (9.7–36.1%). We found that the accumulation of large particles on leaves was related to leaf morphology (leaf length), while the accumulation of fine particles was related to leaf chemistry. The mechanisms behind this result need further research. We hypothesize that large particles may mainly be captured by interception, while fine particles may mainly be captured by waxes or deposited in the microstructures (e.g., grooves), which may be related to LNC and LPC. Fine particles are not easily removed, which may be a possible reason for the poor correlation between morphology representing structural stability and fine particle accumulation capacities.

Trees stand regularly occur along roads in many cities, and therefore, quantifying individual-level PM accumulation capacity is needed. We encourage future studies to integrate leaf-level PM accumulation capacity with leaf density and crown size to obtain whole-plant PM accumulation capacity and link it with functional traits of species.

Conclusion

Our results provide encouraging evidence of correlations between species functional traits and abilities to capture airborne particulates, including $PM_{2.5}$, $PM_{2.5-10}$ and $PM_{>10}$. Light saturated photosynthetic capacity per leaf area (J_m) was negatively correlated with all three PM size fractions, indicating that conservative species accumulated larger amounts of PM than acquisitive species. Denser wood species and smaller leaves captured more large particles ($PM_{>10}$), while 'expensive' leaves (high leaf N or leaf P) captured more fine particles ($PM_{2.5}$), indicating different mechanisms for capturing particles of different sizes. Although the correlations between economic traits (specific leaf area and wood density) and PM deposition were weak, our findings highlight the great potential of functional traits as a tool for linking species' efficiency at air purification with their growth strategies and environmental stress tolerances.

Declarations

Ethics approval. Not applicable

Consent to participate. Not applicable

Consent for publication. Not applicable

Competing interests The authors declare that they have no competing interests.

References

1. Adler PB, Salguero-Gómez R, Compagnoni A et al (2014) Functional traits explain variation in plant life history strategies. Proc Natl Acad Sci USA 111:740–745. https://doi.org/10.1073/pnas.1315179111

2. Barwise Y, Kumar P (2020) Designing vegetation barriers for urban air pollution abatement: a practical review for appropriate plant species selection. NPJ Clim Atmos Sci 3:12. https://doi.org/10.1038/s41612-020-0115-3

3. Beckett KP, Freer-Smith PH, Taylor G (2000) Particulate pollution capture by urban trees: effect of species and windspeed. Glob Change Biol 6:995–1003. https://doi.org/10.1046/j.1365-2486.2000.00376.x

4. Burkhardt J, Peters K, Crossley A (1995) The presence of structural surface waxes on coniferousneedles affects the pattern of dry deposition of fine particles. J Exp Bot 46:823–831. https://doi.org/10.1093/jxb/46.7.823

5. Cai M, Xin Z, Yu X (2017) Spatio-temporal variations in PM leaf deposition: A meta-analysis. Environ Pollut 231:207–218. https://doi.org/10.1016/j.envpol.2017.07.105

6. Chaudhary IJ, Rathore D (2018) Suspended particulate matter deposition and its impact on urban trees. Atmospheric Pollut Res 9:1072–1082. https://doi.org/10.1016/j.apr.2018.04.006

7. Chaudhary IJ, Rathore D (2019) Dust pollution: Its removal and effect on foliage physiology of urban trees. Sustain Cities Soc 51:101696. https://doi.org/10.1016/j.scs.2019.101696

8. Chave J, Coomes D, Jansen S et al (2009) Towards a worldwide wood economics spectrum. Ecol Lett 12:351–366. https://doi.org/10.1111/j.1461-0248.2009.01285.x

9. Chen X, Zhou Z, Teng M et al (2015) Accumulation of three different sizes of particulate matter on plant leaf surfaces: Effect on leaf traits. Arch biol sci (Beogr) 67:1257–1267. https://doi.org/10.2298/ABS150325102C

10. Chen Y (2015) Intraspecific foliar PH variation and traits correlation patterns. Masters' thesis, Sun Yat-sen University

11. Chiam Z, Song XP, Lai HR, Tan HTW (2019) Particulate matter mitigation via plants: Understanding complex relationships with leaf traits. Sci Total Environ 688:398–408. https://doi.org/10.1016/j.scitotenv.2019.06.263

12. Dzierżanowski K, Popek R, Gawrońska H et al (2011) Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Waxes of Urban Forest Species. Int J Phytoremediation 13:1037–1046. https://doi.org/10.1080/15226514.2011.552929

13. Feng J, Zhao K, He D et al (2018) Comparing shade tolerance measures of woody forest species. PeerJ 6:e5736. https://doi.org/10.7717/peerj.5736

14. Firn J, McGree JM, Harvey E et al (2019) Leaf nutrients, not specific leaf area, are consistent indicators of elevated nutrient inputs. Nat Ecol Evol 3:400–406. https://doi.org/10.1038/s41559-018-0790-1

15. Freer-Smith PH, Beckett KP, 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. Environ Pollut 133:157–167. https://doi.org/10.1016/j.envpol.2004.03.031

16. He D, Chen Y, Zhao K et al (2018) Intra- and interspecific trait variations reveal functional relationships between specific leaf area and soil niche within a subtropical forest. Ann Bot 121:1173–1182. https://doi.org/10.1093/aob/mcx222

17. Hetherington AM, Woodward FI (2003) The role of stomata in sensing and driving environmental change. Nature 424:901–908. https://doi.org/10.1038/nature01843

18. Hiemstra PH, Pebesma EJ, Twenhöfel CJW, Heuvelink GBM (2009) Real-time automatic interpolation of ambient gamma dose rates from the Dutch radioactivity monitoring network. Comput Geosci 35:1711–1721. https://doi.org/10.1016/j.cageo.2008.10.011

19. Hwang H-J, Yook S-J, Ahn K-H (2011) Experimental investigation of submicron and ultrafine soot particle removal by tree leaves. Atmos Environ 45:6987–6994. https://doi.org/10.1016/j.atmosenv.2011.09.019

20. Janhäll S (2015) Review on urban vegetation and particle air pollution – Deposition and dispersion. Atmos Environ 105:130–137. https://doi.org/10.1016/j.atmosenv.2015.01.052

21. Kitajima K (1994) Relative importance of photosynthetic traits and allocation patterns as correlates of seedling shade tolerance of 13 tropical trees. Oecologia 98:419–428. https://doi.org/10.1007/BF00324232

22. Leonard RJ, McArthur C, Hochuli DF (2016) Particulate matter deposition on roadside plants and the importance of leaf trait combinations. Urban For Urban Green 20:249–253. https://doi.org/10.1016/j.ufug.2016.09.008

23. Lewis M, Schupp E, Monaco T (2017) Road Dust Correlated with Decreased Reproduction of the Endangered Utah Shrub Hesperidanthus suffrutescens. Western North American Naturalist 77:430–439. https://doi.org/10.3398/064.077.0404

24. Li Y, Jiang Y, Shipley B et al (2021) The complexity of trait–environment performance landscapes in a local subtropical forest. New Phytol 229:1388–1397. https://doi.org/10.1111/nph.16955

25. Liang D, Ma C, Wang Y et al (2016) Quantifying PM2.5 capture capability of greening trees based on leaf factors analyzing. Environ Sci Pollut Res 23:21176–21186. https://doi.org/10.1007/s11356-016-7687-9

26. Litschke T, Kuttler W (2008) On the reduction of urban particle concentration by vegetation - A review. Meteorol Z 17:229–240. https://doi.org/10.1127/0941-2948/2008/0284

27. Liu C, Li Y, Yan P, He N (2021) How to Improve the Predictions of Plant Functional Traits on Ecosystem Functioning? Front Plant Sci 12:622260. https://doi.org/10.3389/fpls.2021.622260

28. Liu J, Cao Z, Zou S et al (2018) An investigation of the leaf retention capacity, efficiency and mechanism for atmospheric particulate matter of five greening tree species in Beijing, China. Sci Total Environ 616–617:417–426. https://doi.org/10.1016/j.scitotenv.2017.10.314

29. Liu L, Guan D, Peart MR et al (2013) The dust retention capacities of urban vegetation—a case study of Guangzhou, South China. Environ Sci Pollut Res 20:6601–6610. https://doi.org/10.1007/s11356-013-1648-3

30. Liu L, Guan D, Peart MR (2012) The morphological structure of leaves and the dust-retaining capability of afforested plants in urban Guangzhou, South China. Environ Sci Pollut Res 19:3440–3449. https://doi.org/10.1007/s11356-012-0876-2

31. Liu Y, Yang Z, Zhu M, Yin J (2019) Size fractions of dust and amount of associated metals on leaf surface and inner wax of 15 plant species at Beijing roadside. Int J Phytoremediation 21:334–351. https://doi.org/10.1080/15226514.2018.1524834

32. Lohbeck M, Poorter L, Lebrija-Trejos E et al (2013) Successional changes in functional composition contrast for dry and wet tropical forest. Ecology 94:1211–1216. https://doi.org/10.1890/12-1850.1

33. Luo J, Niu Y, Zhang Y et al (2020) Dynamic analysis of retention PM $_{2.5}$ by plant leaves in rainfall weather conditions of six tree species. Energy Sour Part A Recover Utilization Environ Eff 42:1014–1025. https://doi.org/10.1080/15567036.2019.1602212

34. Nguyen T, Yu X, Zhang Z et al (2015) Relationship between types of urban forest and PM2.5 capture at three growth stages of leaves. J Environ Sci 27:33–41. https://doi.org/10.1016/j.jes.2014.04.019

35. Poorter L, Wright SJ, Paz H et al (2008) Are functional traits good predictors of demographic rates? Evidence from five neotropical forests. Ecology 89:1908–1920

36. Przybysz A, Popek R, Stankiewicz-Kosyl M et al (2021) Where trees cannot grow – Particulate matter accumulation by urban meadows. Sci Total Environ 785:147310. https://doi.org/10.1016/j.scitotenv.2021.147310

37. Przybysz A, Sæbø A, Hanslin HM, Gawroński SW (2014) Accumulation of particulate matter and trace elements on vegetation as affected by pollution level, rainfall and the passage of time. Sci Total Environ 481:360–369. https://doi.org/10.1016/j.scitotenv.2014.02.072

38. R Development Core Team (2016) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

39. Räsänen JV, Holopainen T, Joutsensaari J et al (2013) Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees. Environ Pollut 183:64–70. https://doi.org/10.1016/j.envpol.2013.05.015

40. Rascher U, Liebig M, Luttge U (2000) Evaluation of instant light-response curves of chlorophyll fluorescence parameters obtained with a portable chlorophyll fluorometer on site in the field. Plant Cell Environ 23:1397–1405. https://doi.org/10.1046/j.1365-3040.2000.00650.x

41. Reich PB (2014) The world-wide 'fast–slow' plant economics spectrum: a traits manifesto. J Ecol 102:275–301. https://doi.org/10.1111/1365-2745.12211

42. Reich PB, Uhl C, Walters MB, Ellsworth DS (1991) Leaf lifespan as a determinant of leaf structure and function among 23 amazonian tree species. Oecologia 86:16–24. https://doi.org/10.1007/BF00317383

43. Reich PB, Wright IJ, Cavender-Bares J et al (2003) The Evolution of Plant Functional Variation: Traits, Spectra, and Strategies. Int J Plant Sci 164:S143–S164. https://doi.org/10.1086/374368

44. Sæbø A, Popek R, Nawrot B et al (2012) Plant species differences in particulate matter accumulation on leaf surfaces. Sci Total Environ 427–428:347–354. https://doi.org/10.1016/j.scitotenv.2012.03.084

45. Shao F, Wang L, Sun F et al (2019) Study on different particulate matter retention capacities of the leaf surfaces of eight common garden plants in Hangzhou, China. Sci Total Environ 652:939–951. https://doi.org/10.1016/j.scitotenv.2018.10.182

46. Shi J, Zhang G, An H et al (2017) Quantifying the particulate matter accumulation on leaf surfaces of urban plants in Beijing, China. Atmospheric Pollut Res 8:836–842. https://doi.org/10.1016/j.apr.2017.01.011

47. Siefert A, Violle C, Chalmandrier L et al (2015) A global meta-analysis of the relative extent of intraspecific trait variation in plant communities. Ecol Lett 18:1406–1419. https://doi.org/10.1111/ele.12508

48. Simon E, Harangi S, Baranyai E et al (2016) Influence of past industry and urbanization on elemental concentrations in deposited dust and tree leaf tissue. Urban For Urban Green 20:12–19. https://doi.org/10.1016/j.ufug.2016.07.017

49. Sun X, Li H, Guo X et al (2018) Capacity of six shrub species to retain atmospheric particulates with different diameters. Environ Sci Pollut Res 25:2643–2650. https://doi.org/10.1007/s11356-017-0549-2

50. Sun Y, Lin W, Li Y, Xu D (2020) Dust deposition on vegetation leaves in Shanghai, China. International Journal of Environmental Health Research 1–14. https://doi.org/10.1080/09603123.2020.1714559

51. Valladares F, Niinemets Ü (2008) Shade Tolerance, a Key Plant Feature of Complex Nature and Consequences. Ann Rev Ecol Evol Syst 39:237–257. https://doi.org/10.1146/annurev.ecolsys.39.110707.173506

52. Walters MB, Reich PB (1999) Low-light carbon balance and shade tolerance in the seedlings of woody plants: do winter deciduous and broad-leaved evergreen species differ? New Phytol 143:143–154. https://doi.org/10.1046/j.1469-8137.1999.00425.x

53. Wang H, Shi H, Li Y et al (2013) Seasonal variations in leaf capturing of particulate matter, surface wettability and micromorphology in urban tree species. Front Env Sci Eng 7:579–588. https://doi.org/10.1007/s11783-013-0524-1

54. Weerakkody U, Dover JW, Mitchell P, Reiling K (2018a) Quantification of the traffic-generated particulate matter capture by plant species in a living wall and evaluation of the important leaf characteristics. Sci Total Environ 635:1012–1024. https://doi.org/10.1016/j.scitotenv.2018.04.106

55. Weerakkody U, Dover JW, Mitchell P, Reiling K (2018b) Evaluating the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves. Urban For Urban Green 30:98–107. https://doi.org/10.1016/j.ufug.2018.01.001

56. Weerakkody U, Dover JW, Mitchell P, Reiling K (2017) Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. Urban For Urban Green 27:173–186. https://doi.org/10.1016/j.ufug.2017.07.005

57. WHO (2006) WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Global update 2005. Summary of risk assessment. World Health Organization, Geneva

58. Wright IJ, Ackerly DD, Bongers F et al (2007) Relationships Among Ecologically Important Dimensions of Plant Trait Variation in Seven Neotropical Forests. Ann Bot 99:1003–1015. https://doi.org/10.1093/aob/mcl066

59. Wright IJ, Reich PB, Westoby M et al (2004) The worldwide leaf economics spectrum. Nature 428:821–827. https://doi.org/10.1038/nature02403

60. Wright SJ, Kitajima K, Kraft NJB et al (2010) Functional traits and the growth–mortality trade-off in tropical trees. Ecology 91:3664–3674. https://doi.org/10.1890/09-2335.1

61. Xu X, Xia J, Gao Y, Zheng W (2020) Additional focus on particulate matter wash-off events from leaves is required: A review of studies of urban plants used to reduce airborne particulate matter pollution. Urban For Urban Green 48:126559. https://doi.org/10.1016/j.ufug.2019.126559

62. Xu X, Zhang Z, Bao L et al (2017) Influence of rainfall duration and intensity on particulate matter removal from plant leaves. Sci Total Environ 609:11–16. https://doi.org/10.1016/j.scitotenv.2017.07.141

63. Xu Y, Xu W, Mo L et al (2018) Quantifying particulate matter accumulated on leaves by 17 species of urban trees in Beijing, China. Environ Sci Pollut Res 25:12545–12556. https://doi.org/10.1007/s11356-018-1478-4

64. Yan S, Cao H, Chen Y et al (2016) Spatial and temporal characteristics of air quality and air pollutants in 2013 in Beijing. Environ Sci Pollut Res 23:13996–14007. https://doi.org/10.1007/s11356-016-6518-3

65. Yu W, Wang Y, Wang Y et al (2018) Application of a coupled model of photosynthesis and stomatal conductance for estimating plant physiological response to pollution by fine particulate matter (PM2.5). Environ Sci Pollut Res 25:19826–19835. https://doi.org/10.1007/s11356-018-2128-6

66. Zhang W, Wang B, Niu X (2017) Relationship between Leaf Surface Characteristics and Particle Capturing Capacities of Different Tree Species in Beijing. https://doi.org/10.3390/f8030092. Forests 8:

67. Zhao K, He F (2016) Estimating light environment in forests with a new thresholding method for hemispherical photography. Can J For Res 46:1103–1110. https://doi.org/10.1139/cjfr-2016-0003

68. Zhu J, Yu Q, Zhu H et al (2019) Response of dust particle pollution and construction of a leaf dust deposition prediction model based on leaf reflection spectrum characteristics. Environ Sci Pollut Res 26:36764–36775. https://doi.org/10.1007/s11356-019-06635-4

Tables

Table 1

Summary of the 14 species used in this study for which PM accumulation capacity and functional trait data were collected. $PM_{2.5}$, $PM_{2.5-10}$, $PM_{>10}$ per leaf area ($g \cdot m^{-2}$); photosynthetic capacity (J_m, $\mu mol \cdot m^{-2} s^{-1}$); wood density (WD, $g \cdot cm^{-3}$); specific leaf area (SLA, $cm^2 \cdot g^{-1}$); leaf length (LL, cm); leaf nitrogen content (LNC, $g \cdot kg^{-1}$); and leaf phosphorus content (LPC, $g \cdot kg^{-1}$) are illustrated (mean ± SD).

Species (Family)	PM$_{2.5}$ (g·m^{-2})	PM$_{2.5-10}$ (g·m^{-2})	PM$_{>10}$ (g·m^{-2})	J$_m$ (µmol·m^{-2} s^{-1})	WD (g·cm^{-3})	SLA (cm^2·g^{-1})	LL (cm)	LNC (g·kg^{-1})	LPC (g·kg^{-1})
Cryptocarya concinna (Lauraceae)	0.82 ± 0.13	1.29 ± 0.41	2.01 ± 1.50	33 ± 17.3	0.56 ± 0.08	143.3 ± 49.5	9.2 ± 1.6	18.3 ± 2.0	0.67 ± 0.32
Xanthophyllum hainanense (Polygalaceae)	0.55 ± 0.24	0.88 ± 0.37	2.44 ± 0.56	34.1 ± 13.7	0.71 ± 0.09	149 ± 17.6	7.6 ± 1.3	22.2 ± 2.5	0.66 ± 0.07
Castanopsis chinensis (Fagaceae)	0.31 ± 0.16	0.64 ± 0.44	1.69 ± 0.84	49.4 ± 19.2	0.6 ± 0.07	110.7 ± 25.1	8.5 ± 2.5	12.8 ± 2.5	0.41 ± 0.08
Lindera chunii (Lauraceae)	0.31 ± 0.06	0.61 ± 0.22	1.63 ± 0.22	42 ± 16.3	0.56 ± 0.07	161.5 ± 29.2	10.2 ± 1.2	15 ± 1.9	0.72 ± 0.13
Rapanea neriifolia (Myrsinaceae)	0.25 ± 0.08	0.89 ± 0.21	1.39 ± 0.26	43.2 ± 17.4	0.71 ± 0.08	101.5 ± 18.5	13.2 ± 2.8	8.8 ± 1.6	0.37 ± 0.07
Ardisia quinquegona (Myrsinaceae)	0.34 ± 0.08	0.77 ± 0.38	1.35 ± 0.35	40.2 ± 24.1	0.57 ± 0.07	149.1 ± 30.4	11.8 ± 1.9	15.4 ± 1.1	0.54 ± 0.08
Machilus breviflora (Lauraceae)	0.33 ± 0.12	0.24 ± 0.00	1.62 ± 0.29	40.9 ± 12.0	0.58 ± 0.09	102.9 ± 15.4	10.1 ± 0.9	10.5 ± 0.8	0.44 ± 0.10
Canarium album (Burseraceae)	0.7 ± 0.06	0.26 ± 0.03	0.98 ± 0.17	44.3 ± 23.2	0.33 ± 0.08	219.7 ± 54	19.9 ± 4.1	20 ± 2.8	1.02 ± 0.23
Schima superb (Theaceae)	0.2 ± 0.03	0.27 ± 0.14	1.43 ± 0.42	56.1 ± 10.8	0.64 ± 0.08	109.9 ± 23.5	14.7 ± 2.0	11.5 ± 1.6	0.31 ± 0.06
Symplocos congesta (Symplocaceae)	0.24 ± 0.07	0.67 ± 0.16	0.97 ± 0.22	55.8 ± 21.3	0.53 ± 0.06	119 ± 20.6	13.9 ± 2.7	11.4 ± 1.4	0.37 ± 0.08
Lithocarpus calophyllus (Fagaceae)	0.27 ± 0.02	0.31 ± 0.09	1.13 ± 0.08	50.3 ± 17.5	0.63 ± 0.07	105.9 ± 21.3	16.2 ± 2.7	12.1 ± 1.7	0.55 ± 0.16
Itea chinensis (Saxifragaceae)	0.19 ± 0.03	0.24 ± 0.15	1.23 ± 0.39	73.9 ± 25.4	0.57 ± 0.06	178.5 ± 36.7	11.4 ± 1.3	15 ± 2.0	0.69 ± 0.20
Machilus litseifolia	0.27 ± 0.05	0.12 ± 0.04	1.17 ± 0.49	60.5 ± 17.2	0.55 ± 0.09	115.9 ± 28.3	15.1 ±	10.8 ± 2.2	0.44 ± 0.09

(Lauraceae)								2.7	
Schefflera octophylla	0.17 ± 0.01	0.32 ± 0.15	0.97 ± 0.23	58.6 ± 25.9	0.29 ± 0.06	179.8 ± 46	16 ± 3.5	13.7 ± 1.6	0.6 ± 0.1
(Araliaceae)									

Figures

Cryptocarya concinna
Xanthophyllum hainanense
Castanopsis carlesii
Lindera chunii
Myrsine seguinii
Ardisia quinquegona
Machilus breviflora
Canarium album
Schima superba
Symplocos congesta
Lithocarpus crassifolius
Itea chinensis
Machilus litseifolia
Schefflera octophylla
5cm
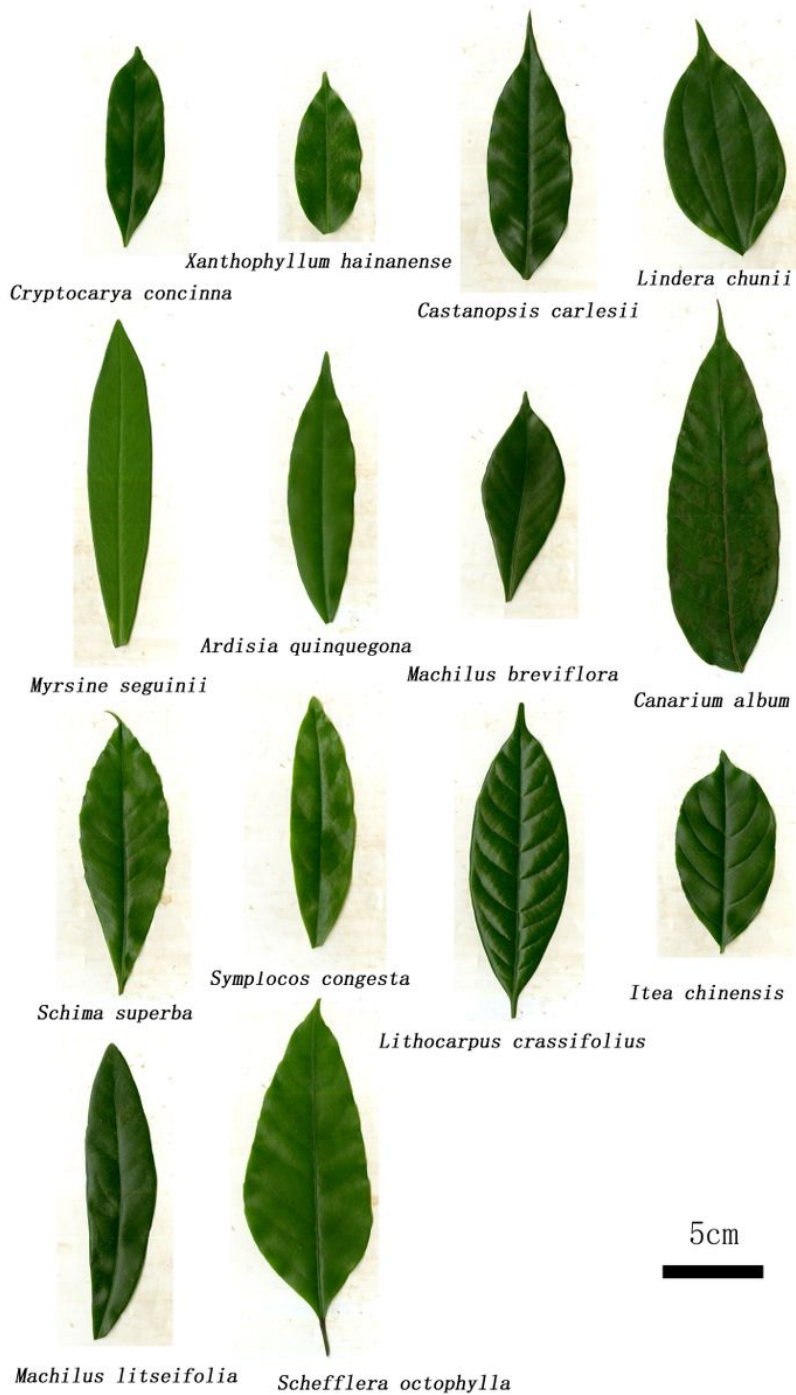
Figure 1

Leaves of the fourteen tree species tested in the study. The species are ordered based on their total suspended particle accumulation capacity of per leaf area
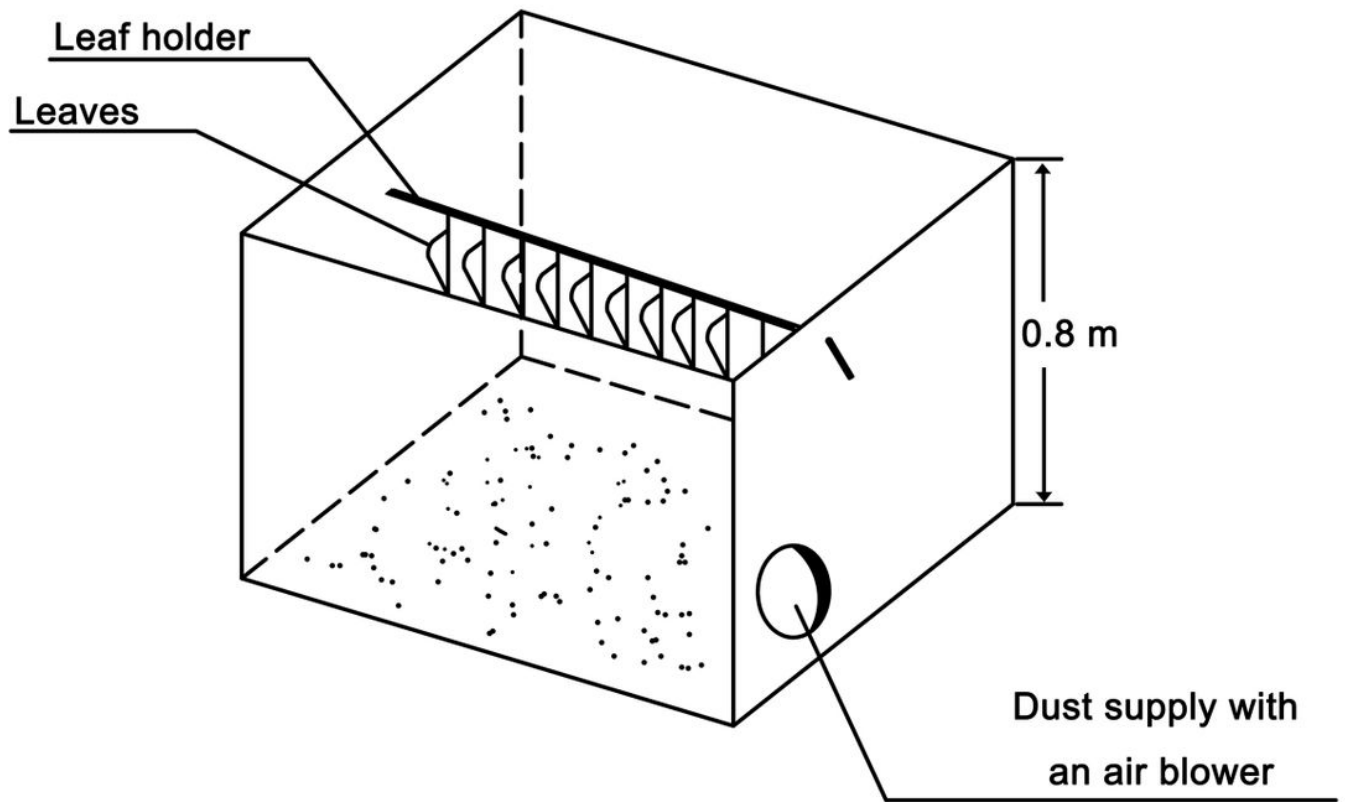
Figure 2

Schematic diagram of the experimental dust box used in this study. Leaves in the box were vertically arranged
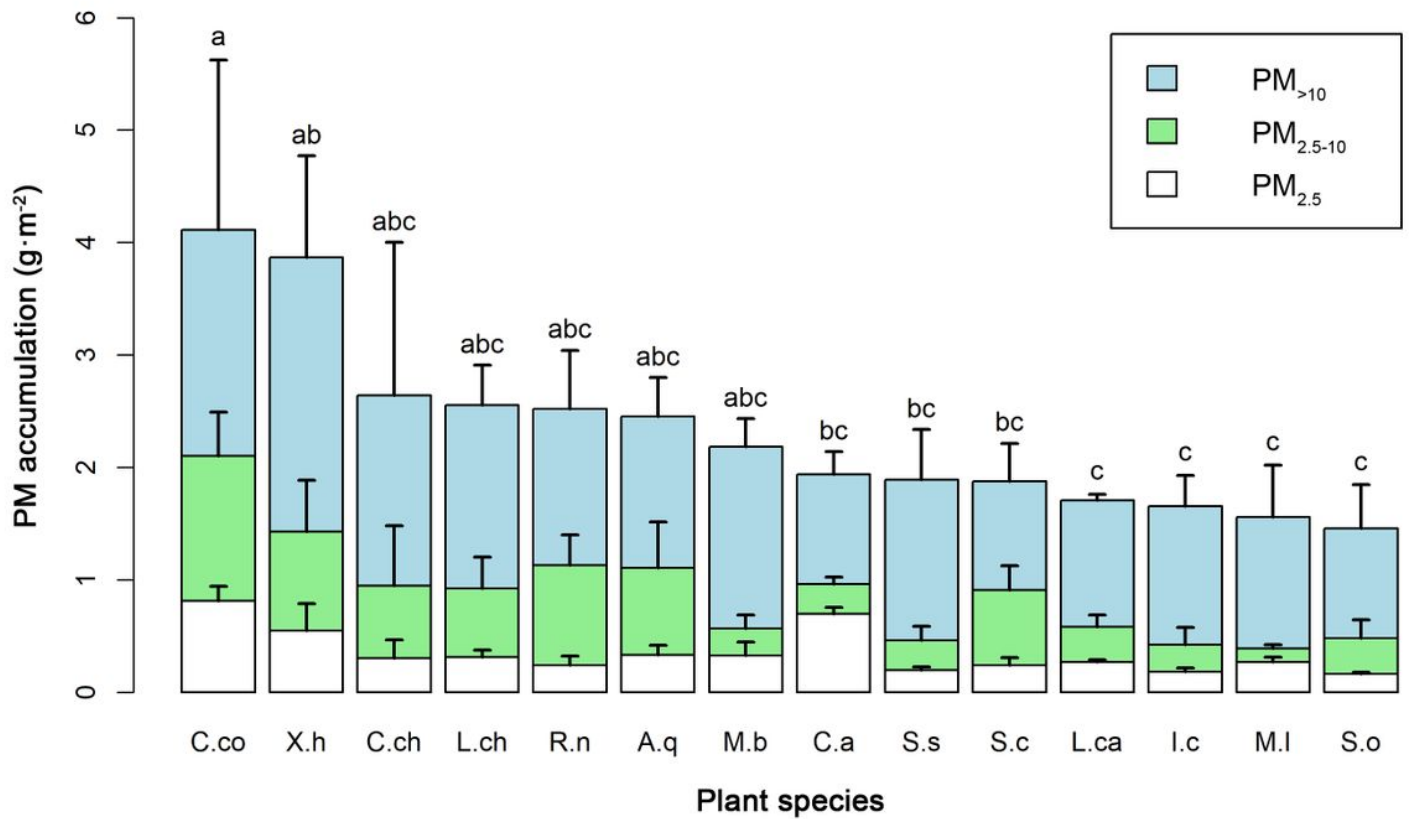
Figure 3

PM captured per leaf area by different species of plants in the experiment. Data are arranged in descending order of total suspended particles (TSP); for an explanation of the species codes, see Table 1. Error bars for $PM_{2.5}$, PM_{10} and TSP are presented. Different letters above the column indicate a significant difference in TSP accumulation per leaf area ($P < 0.05$)
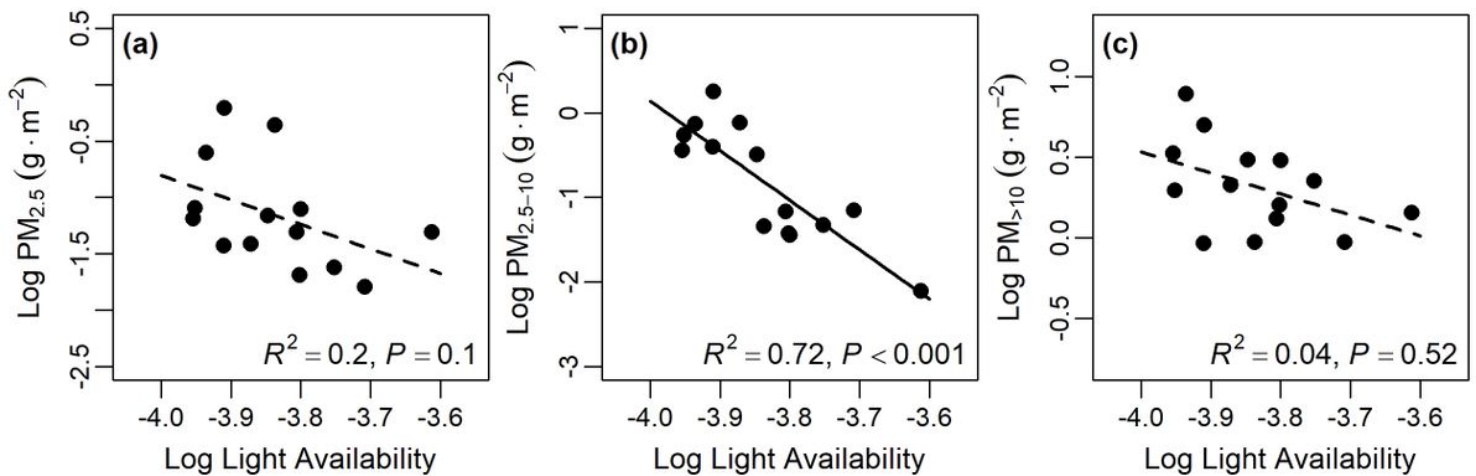
Figure 4

Relationships between shade tolerance (minimum light requirements) and PM capturing capacities of individual species for (a) $PM_{2.5}$, (b) $PM_{2.5-10}$, and (c) $PM_{>10}$. The light availability of each of at least 200 individuals was

quantified for each species, and shade tolerance was calculated as the 10th percentile of species distribution in relation to light availability
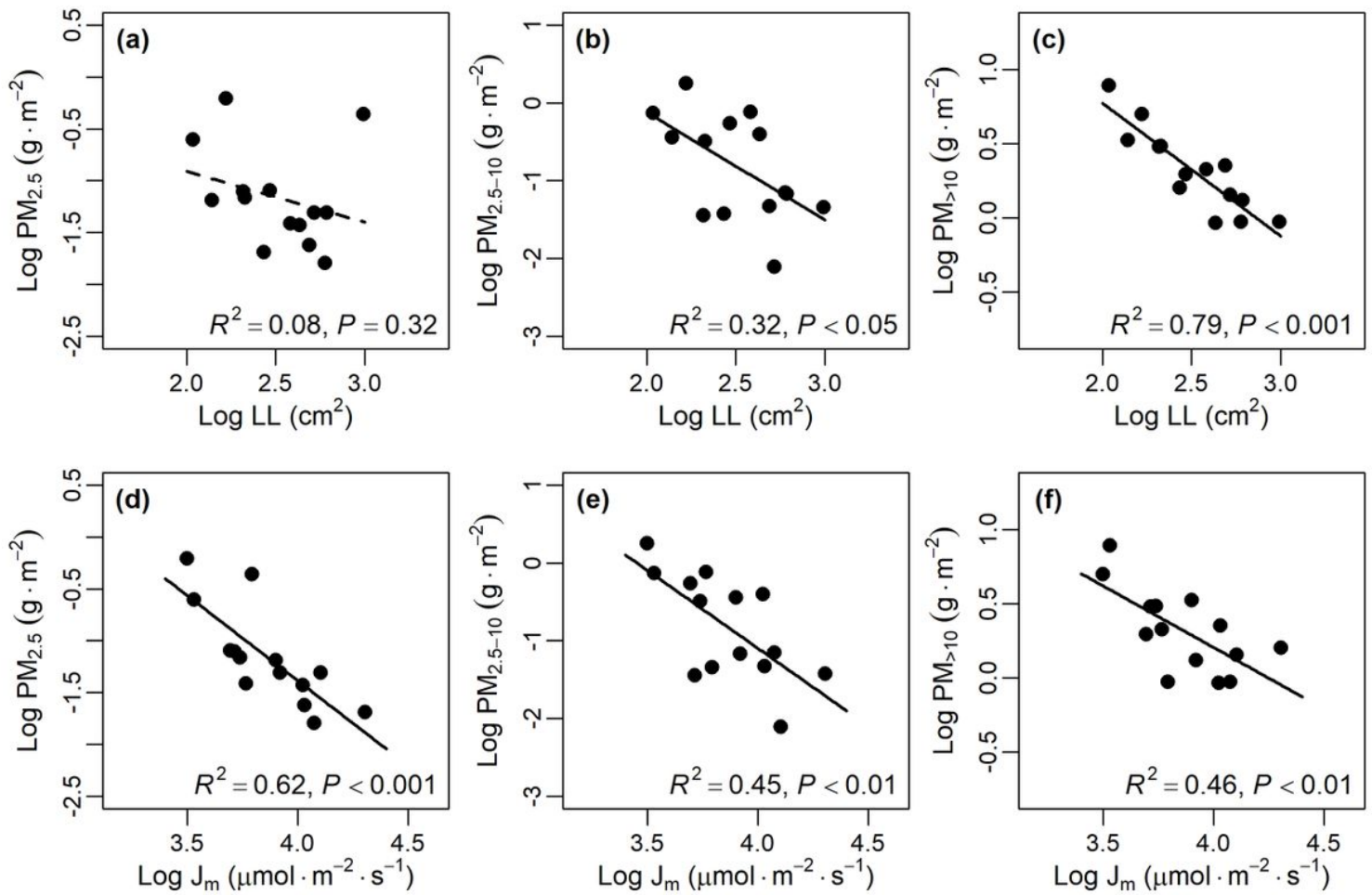

Figure 5

Relationships between plant traits and PM capturing capacities of individual species: (a) leaf length and $PM_{2.5}$, (b) leaf length and $PM_{2.5-10}$, and leaf length and $PM_{>10}$, (d) maximum rate of electron transport (J_m) and $PM_{2.5}$, (e) J_m and $PM_{2.5-10}$ and (f) J_m and $PM_{>10}$. A dashed line denotes a nonsignificant relationship between trait and PM capturing abilities
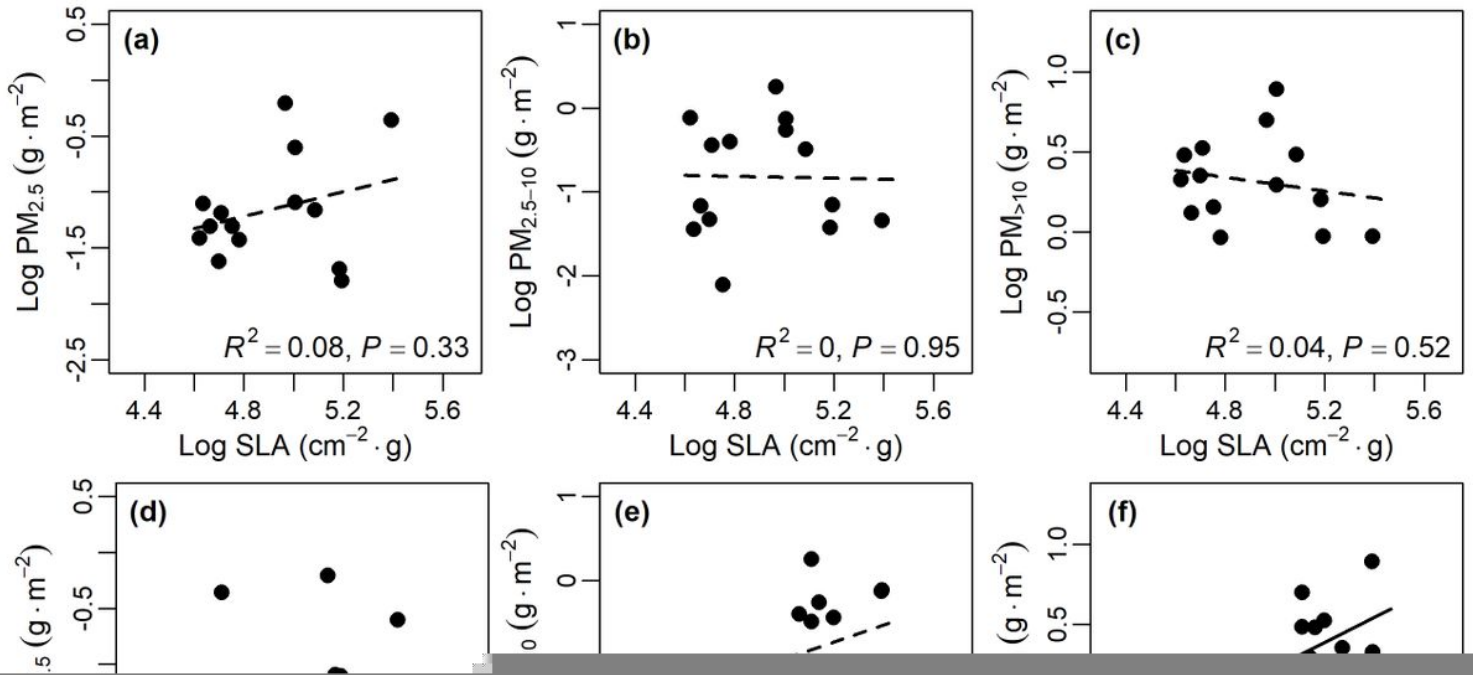
Figure 6

Relationships between economic traits and the PM capturing abilities of individual species: (a) SLA and $PM_{2.5}$, (b) SLA and $PM_{2.5-10}$, (c) SLA and $PM_{>10}$, (d) WD and $PM_{2.5}$, (e) WD and $PM_{2.5-10}$ and (f) WD and $PM_{>10}$. A dashed line denotes a nonsignificant relationship between trait and PM capturing abilities
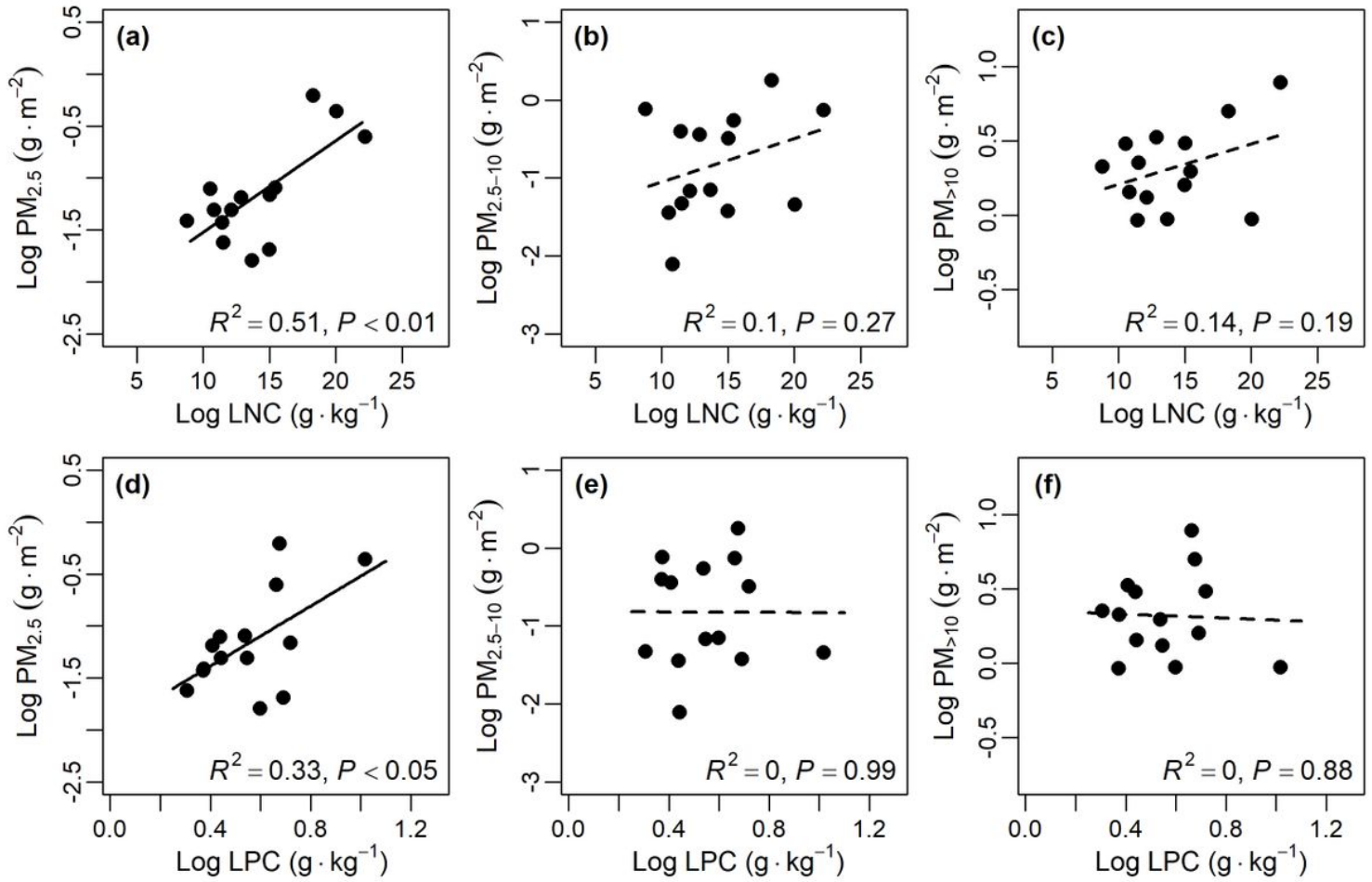
Figure 7

Relationships between leaf chemistry and PM capturing abilities of individual species: (a) leaf nitrogen content (LNC) and $PM_{2.5}$, (b) LNC and $PM_{2.5-10}$, (c) LNC and $PM_{>10}$, (d) leaf phosphorus content (LPC) and $PM_{2.5}$, (e) LPC and $PM_{2.5-10}$ and (f) LPC and $PM_{>10}$. A dashed line denotes a nonsignificant relationship between trait and PM capturing abilities

Figure 8

Path diagram representing how leaf nitrogen content (LNC), leaf phosphorus content (LPC), specific leaf area (SLA), wood density (WD), leaf length (LL) and maximum rate of electron transport (J_m) influence species abilities to capture fine ($PM_{2.5}$), coarse ($PM_{2.5-10}$) and large ($PM_{>10}$) particulates in the fourteen species tested in this study. The model was tested with Fisher's C statistic, test statistic = 11.12 with 14 model degrees of freedom and $P = 0.676$ (indicating close model-data fit). Path coefficients were calculated based on standardized values. Solid lines represent positive paths, and dashed lines represent negative paths. Asterisks denote significance: ***, $P < 0.001$; **, $P < 0.01$; *, $P < 0.05$. Nonsignificant paths were excluded from the model