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Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees

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Concise Title: Capability of trees to remove fine particles from air

Informative Title: Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees

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Abstract

Trees can improve air quality by capturing particles in their foliage. We determined the particle capture efficiencies of coniferous *Pinus sylvestris* and three broadleaved species: *Betula pendula*, *Betula pubescens* and *Tilia vulgaris* in a wind tunnel using NaCl particles. The importance of leaf surface structure, physiology and moderate soil drought on the particle capture efficiencies of the trees were determined. The results confirm earlier findings of more efficient particle capture by conifers compared to broadleaved plants. The particle capture efficiency of *P. sylvestris* (0.21%) was significantly higher than those of *B. pubescens, T. vulgaris* and *B. pendula* (0.083%, 0.047%, 0.043%, respectively). The small leaf size of *P. sylvestris* was the major characteristic that increased particle capture. Among the broadleaved species, low leaf wettability, low stomatal density and leaf hairiness increased particle capture. Moderate soil drought tended to increase particle capture efficiency of *P. sylvestris*.

Keywords: Fine particles; capture efficiency; trees; wind tunnel; moderate drought

Capsule: Trees can improve air quality by removing $PM_{2.5}$ pollutants carried on the wind at a velocity of 3 m s^{-1}, the efficiency of which depends on species leaf characteristics and physical factors.

Introduction

Trees can capture particulate matter (PM) in the air, thus improving air quality (McPherson et al., 2005; Nowak et al., 2006). Atmospheric particles can be from several sources, both of natural and anthropogenic origin (Song et al., 2001; Mueller and Mallard, 2011). PM pollutants are known to be harmful to human health (Pope III and Dockery, 2006), but at higher exposure levels they can also be harmful to vegetation and cause growth reduction (Grantz et al., 2003). The most negative human health effects have been linked to particles smaller than 2.5 µm ($PM_{2.5}$) (Schwartz et al., 1996).

The extent of particle deposition to the tree canopy is often defined by particle capture efficiency (Cp); the percentage of particles deposited on leaf surfaces of those available for deposition (Belot and Gauthier, 1975; Beckett et al., 2000). Deposition velocity (Vg, m s^{-1} or cm s^{-1}) also describes the rate of deposition (Belot and Gauthier, 1975; Beckett et al., 2000). Recent studies on the Cp of coniferous and broadleaved tree species show high variation that is dependent on wind speed, particle size and biological and physical properties of the trees. The suggested mechanisms of particle deposition on leaf surfaces depend mostly on particle size and their velocity (Hinds, 1999). The most efficient deposition mechanism for particles smaller than 0.5µm is Brownian diffusion (Hinds, 1999). Particles larger than 0.5µm are mainly deposited by impaction, and interception (Hinds, 1999). Increasing wind velocity typically enhances particle deposition to leaf surfaces, which is in line with the theory of the deposition mechanisms (Hinds, 1999;

Beckett et al., 2000; Freer-Smith et al., 2004; Reinap et al., 2009). Ultra-fine particles ($PM_{0.1}$) showed increasing levels of deposition to *Pinus taeda* and *Juniperus chinensis* with decreasing particle size, as is expected when Brownian diffusion is the main deposition mechanism (Hinds, 1999; Lin and Khlystov, 2012). The orientation of branches of coniferous species does not significantly affect the capturing efficiency of $PM_{2.5}$ or $PM_{0.1}$ particles (Lin and Khlystov, 2012; Räsänen et al., 2012).

Leaf anatomy can be a significant factor affecting particle deposition. For example, a small leaf area and a high amount of structural wax (conifers) have been suggested to increase particle deposition on leaf surfaces (Wedding et al., 1975; Burkhardt et al., 1995; Beckett et al., 2000). Leaf hairs are obstacles to particles, similar to fibers of filters, and thus efficiently increase particle deposition compared to flat surfaces (Wedding et al., 1975; Little, 1977). A higher Cp of drought-treated *Picea abies* was connected to low stomatal transpiration and conductance (Räsänen et al., 2012), but not to stomatal density or wax layer condition, which were not affected by short-term drought. The role of stomatal activity in particle deposition is ambiguous because transpiration of water through stomata cools the surface and thus attracts fine particles, but at the same time transpired water repels fine particles due to diffusiophoresis (Burkhardt et al., 1995; Hinds, 1999). Overall, Cp has been reported to vary between 0.03% and 0.38% among Corsican pine (*Pinus nigra* var. *maritima*), cypress (× *Cupressocyparis leylandii*), maple (*Acer campestre*), whitebeam (*Sorbus intermedia*) and poplar (*Populus deltoides* × *trichocarpa*) studied with a 3 m s^{-1} wind flow (Beckett et al., 2000). With a similar test arrangement oak (*Quercus petraea*), alder (*Alnus glutinosa*), ash (*Fraxinus excelsior*), sycamore (*Acer pseudo-platanus*), Douglas fir

(*Pseudotsuga menziesii*), weeping fig (*Ficus nitida*) and eucalyptus (*Eucalyptus globulus*) produced Cp values from 0.01% to 0.42% (Freer-Smith et al., 2004). The Cp measured for *Picea abies* was from 0.05% to 0.07% depending on its soil water content (Räsänen et al., 2012). At a lower wind flow of 2 m s^{-1}, Reinap et al. (2009) recorded a Cp of 0.01% for *Quercus robur*. In the above mentioned studies different methods to calculate Cp values for trees have been used, including foliage silhouette area (Belot and Gauthier, 1975), leaf or needle one-sided projection areas (Beckett et al., 2000; Freer-Smith et al., 2004; Reinap et al., 2009) and total leaf or needle area (Räsänen et al., 2012). The methodology related to leaf area calculation is further discussed in this paper.

In this study our aim was to determine the Cp and Vg values for four tree species that have not or have rarely been studied before. We have modified the method to calculate Cp and Vg so that it takes total surface area into account (Räsänen et al. 2012) and thus balances comparison of broadleaved and coniferous species. Furthermore, the influence of several anatomical or physiological leaf characteristics on Cp were studied, e.g. stomatal density, stoma diameter, stomatal conductance, transpiration, unit leaf area, wettability (contact angle), abundance of trichomes and hairs. In order to study the importance of these leaf characteristics, the data were analyzed in detail using multivariate data analyses. Coniferous Scots pine (*Pinus sylvestris*) and three broadleaved species: silver birch (*Betula pendula*), pubescent birch (*Betula pubescens*) and common lime (*Tilia vulgaris*) were selected as test species due to their prevalence in northern forests and built-up environments. Our previous study showed that moderate soil drought increased the Cp of Norway spruce (Räsänen et al., 2012) and here the effect of soil drought was further studied for the four additional species.

Material and methods

Plant material

Saplings of one year old Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth), pubescent birch (*Betula pubescens* Ehrh.) and common lime (*Tilia vulgaris* Hayne) were used as test species in this study. Scots pine and silver birch were provided by the Finnish Forest Research Institute, Suonenjoki research unit, Finland, whereas pubescent birch were from Taimityllilä Ltd., Mäntyharju, Finland, and common limes were provided by the city garden of Kuopio, Finland. All the saplings, excluding common lime, were repotted after transportation to the research garden of the University of Eastern Finland, Kuopio campus, in May 2009. A peat:sand mixture of 2:1 was used in two liter pots and an additional 1 g N:P:K (9:3.5:5) slow release fertilizer was included. Common limes were potted in two liter pots with a similar mix of peat and sand to the other species. All the saplings were moved inside the greenhouse and watered to prevent drought, and fertilized once a week with 0.1% N:P:K (11:4:25) fertilizer. Saplings were maintained for six to ten weeks until transportation to growth chambers one week before the experiment started.

Growth chambers were adjusted to have a standard relative humidity (RH) of 52%. Lights were off from 23:00-01:00 after which the illumination level started to rise until 06:00 when it reached a maximum PAR level of 375 µmol m^{-2} s^{-1}, this level was maintained until 18:00 and then decreased gradually until darkness at 23:00. The chamber temperature was13 ºC from 00:00 to 01:00 and decreased to 12 ºC from 00:00 to 04:00 and then linearly increased to a maximum level of 19 ºC by 10:00. Temperature started to decrease linearly towards 12 ºC at 18:00. Light and temperature conditions simulated typical conditions of June in Finland.

To study the effect of soil moisture on particle capture efficiency, saplings were divided into two watering treatments one week before the experiment started: well watered and reduced water. Both groups consisted of 12 saplings per species except the common lime groups, which included 10 saplings. Half of the saplings were used as controls and underwent the same treatment, but with no particle exposure (see below). Soil moisture was measured daily (ThetaProbe, Delta-T Devices Ltd., Cambridge, UK) with well watered saplings watered when soil moisture decreased below a 40% limit and reduced water treated watered when moisture went below a 10% limit (Table 1). Saplings were used in experiments one species at a time and all the groups (water treatments, particle exposure/control) were represented similarly during certain times of the day. Saplings were randomly picked for the test from the two watering treatment groups.

Fine particle exposures

Six saplings for each of the four tree species grown in each of the two different soil moisture treatments were exposed to fine particles one by one in wind tunnel experiments during July and August 2009 in order to investigate the particle capture efficiencies (Cp) of each species. Six saplings for each species and drought treatment were also used as controls without particle exposure. The wind tunnel system has been described in more detail by Räsänen *et al.* (2012) and is only briefly described here. A straight duct wind tunnel with a total length of 6 m and a diameter of 0.50 m was utilized to transmit particles towards saplings with a turbulent (Reynolds number 100 000, Hinds (1999)) air flow of 3 m s^{-1}. Air flow was measured log-linearly at six points (2, 7, 16, 34, 43 and 48 cm) from top to bottom of the wind tunnel centre line. An aerosol generator (TSI 9306 Six-Jet Atomizer, TSI Inc., MN, USA) was used to produce fine particles from 10 g l^{-1} NaCl water solution. Particles were fed into the tunnel and smoothly mixed with a fan. An average particle mass concentration of 944 µg m^{-3} in the tunnel air was determined by isokinetic filter collection. The particle generation system is very stable and the particle mass size distribution is unimodal with a geometric mean diameter of 0.7 µm and a geometric standard deviation of 3.0 based on impactor measurements (see Fig. 2b in Räsänen et al., 2012). In total 96% of the particles were in the range of $PM_{2.5}$. The tops of the saplings were placed about 20-40 cm inside the tunnel avoiding leaves from touching the tunnel walls. During the two hour experiment period saplings were illuminated through a transparent section of the tunnel with a greenhouse light (Philips Master Green Power 400 W). Photosynthetically active radiation (PAR, LI-COR, model LI-185B, NE, USA) in the mid-canopy level was kept at 450 µmol m^{-2} s^{-1}. The mean temperature inside the tunnel was 24 ºC and the mean RH was 48% during the experiments.

Analyses of stomatal functioning and fine particle capture

Stomatal conductance (g_s) and transpiration were measured from the saplings placed in the wind tunnel with a porometer (LI-COR, model LI-1600 Steady state porometer, NE, USA) before and after the exposure. The same leaves of the deciduous species or section of the current year Scots pine branches were measured at both time points. The experiment time was recorded as minutes from midnight and it was used in data analysis to investigate if time of the day had an effect on plant activity and thus on particle capture.

To analyze the captured particle mass of each sapling, an average leaf area of 900 cm^2 (20 leaves) or needle area of 300 cm^2 was collected in a beaker and flushed with 40 ml of ion exchanged water for 10 minutes in a shaker (Certomat S, type 886072/6, UK). A syringe was used to collect a sample of the washing water, which was filtered with a 0.40 µm pore size filter and extruded into a sample tube. Ion chromatography (Dionex DX-120 with AS40 autosampler, USA) was used to analyze the chloride ion concentrations in the water. Leaves or needles were scanned and projected leaf area (A_p) was determined with tools in the ImageJ-program (ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA). For broadleaved plants the total leaf area (A_l) was then calculated by multiplying A_p by two. To calculate total surface area of Scots pine needles, ten randomly selected projected needle areas were taken and the total needle length measured. The total needle surface area (A_t, as mm^2) was then calculated by Eq. 1 (Flower-Ellis and Ollson, 1993):

$$A_t = 4.2235 \times L - 15.6835 \quad (1)$$

where L refers to needle length. Calculated A_t values were then compared with A_p values and Eq. 2 was formulated to transform projected area to total needle area (A_n, as mm^2) without laborious needle length measurement.

$$A_n = 3.4794 \times A_p + 516.38 \quad (2)$$

Eq. 2 was utilized instead of Eq. 1 due to its good correlation with A_p ($R^2 = 0.96$) and because of the numerous samples. On average, the A_n was 3.6 times the A_p.

Particle capture efficiency of trees (Cp_{tot}) was calculated by Eq. 3, which was derived from the equation introduced by Beckett et al. (2000):

$$Cp_{tot} = \frac{m}{X_u A} \quad (3)$$

where m is the mass of NaCl accumulated on the total leaf surface during the experimental period, X_u is the NaCl mass per unit area of air flow that passed trees during the experiment (area dose) and A is the total leaf (A_l) or needle area (A_n). Variable X_u is a function of the NaCl mass concentration (c) in the air, the duration of the exposure (t) and the average wind speed (u), i.e. $X_u = ctu$ (Reinap et al., 2009). The unitless ratio of Cp describes the amount of particles collected by the tree compared to those that were available to be captured by the total leaf area. Detectable amounts of NaCl were not found in the washing water of control saplings.

Several different methods have been used for determining leaf surface area in calculations of Cp and Vg, which may influence the results. Belot et al. (1975) used the projected surface of the cross sectional area (silhouette) of trees, which was decreased with increasing wind velocity. This silhouette area of the tree was transformed to total leaf area by multiplying by 5 for coniferous Scots pine (*Pinus sylvestris*) and by 6 for broadleaved oak (*Quercus sessiliflora*) (Belot and Gauthier, 1975). More recent studies have used one-sided scans of leaves detached from the trees to calculate Cp and Vg (Beckett et al., 2000; Freer-Smith et al., 2004; Reinap et al., 2009). Particles are deposited to all sides of the leaf surface, which is equal to a two times greater than projected leaf area of broadleaved trees and over three times greater than projected needle areas of coniferous trees (Flower-Ellis and Ollson, 1993; Freer-Smith et al., 2004; Räsänen et al., 2012). Using one-side areas of the leaves would by error lead to higher values of Cp and Vg for coniferous species than broadleaved trees. Räsänen et al. (2012) derived a method, also used in this study, to calculate Cp by using the total leaf area of the tree, which allows better comparison of coniferous and broadleaved trees (and can also be used to calculate Vg). When results of different studies are compared, the correction of projected area vs. total leaf area is required.

Deposition velocity ($\mathrm{Vg}_{\mathrm{tot}}$, cm s^{-1}) was calculated with the same parameters as $\mathrm{Cp}_{\mathrm{tot}}$ using a formula derived by Beckett et al. (2000), Eq. 4:

$$\mathrm{Vg}_{\mathrm{tot}} = Cp_{tot} \times u \qquad (4)$$

where u is the wind speed.

Unit leaf area (ULA) was calculated by dividing total leaf area by the number of leaves (N_l) with Eq. 5:

$$\mathrm{ULA} = \frac{A}{\mathrm{N_l}} \tag{5}$$

Analyses of leaf surface characteristics

A scanning electron microscope (‘SEM’, Philips XL30 ESEM-TMP, FEI Company, the Netherlands) was utilized to determine leaf surface characteristics. Air-dried samples were coated with a thin (ca. 50 nm) gold-palladium layer (Automatic Sputter Coater B7341, Agar Scientific Ltd., Stansted, UK). Stomatal density (count per mm^2) was determined by calculating the stomata number from a 0.19 mm^2 area of leaf/needle using three sections of each three leaf/needle samples per sapling. The density of hair-like trichomes (hairs) and grandular trichomes (trichomes) were analysed similarly (excluding Scots pine) in an area of 0.19 mm^2 from three leaves per sapling. Epistomatal waxes of Scots pine were classified into five classes representing their distribution and the condition of wax tubes with the method introduced by Turunen and Huttunen (1996): Class 1 having a total coverage (100 %) of perfectly shaped waxes, class 2 less than 30% of wax area damaged and tubes fused, class 3 more than 30% but less than 70% of wax area fused, class 4 more than 70% of wax area fused and class 5 having an almost completely damaged wax area and no wax tubes present. In total, five stomata per needle and three needles per sapling were analyzed (n=15) and the median was calculated. Particle frequency (0 = no particles, 1 = particles) on the stoma area of each tree species were counted from five stomata per leaf and three leaves per sapling (n = 15). Particles were verified with a micro analyzer linked with SEM (Röntec EDS micro analyzer, Röntec GmbH, Germany). The results of particle frequency on stomata were given as a share of the stomata with particles from all the examined stomata.

The wettability of the leaf surface structure was evaluated by contact angle measurements (Turunen and Huttunen, 1996). Three leaves or needles were taken from each sapling and two approximately 5 x 5 mm (needles 5 mm in length) pieces (lower and upper side, for pine convex (lower) side and straight (upper) side) were cut with a razor blade from the middle of each leaf next to the main vein. Pieces were then attached to a plate with double-sided tape. Water droplets of 1 µl were made with a pipette and carefully applied to the leaf surface. A picture of the side profile of the droplet was taken with a camera (Olympus Camedia C-3030 Zoom, Olympus Co., Tokyo, Japan) attached to a microscope (Olympus SZ-PT microscope, Olympus Co., Tokyo, Japan). The angle between the leaf and tangent of the droplet was determined for both right and left sides using computer software (Gimp 2.6, GNU Image Manipulation Program) and the mean value was calculated. Low contact angles were considered to represent more wettable surfaces.

Data analysis

Statistical testing was done with SPSS PASW 18.0 program (SPSS Inc., Chicago, IL, USA). Normality of the collected data was tested with the Shapiro-Wilk test and homogeneity of the variances with Levene’s test to ensure the validity of using parametric tests. Main effects of tree species, watering treatment and their interaction on Cp_{tot} were tested with Two-Way ANOVA. Stomatal conductance and transpiration at the experiment start and end were compared with Paired-Samples T-tests. Comparison of stomatal conductance and transpiration between different watering groups was done with Independent-Samples T-tests. The non-parametric Wilcoxon rank-sum test was used to compare wax classes of the different watering groups of Scots pine.

The importance of measured characteristics on particle capture was studied using multivariate data analyses (Principal Component Analysis - PCA (Wold et al., 1987) and Partial Least Squares Regression – PLS (Martens and Næs, 1989)). PCA and PLS were performed in LatentiX (www.latentix.com) and MATLAB 7.14. There is a total of 1.9% missing values in the data. This was mainly due to technical reasons. These missing values were estimated by local PCAs on each tree species separately, prior to any further analysis by PCA (or PLS). This is to make sure the missing value will not negatively influence the lack of separation of the four tree-species studied in this project. PCA was utilized to find species-specific leaf characteristics. Conductance and transpiration measured after the experiment were omitted from the PCA because of the high correlation with the same variables measured at the beginning of the experiment. A PLS (Partial Least Squares) model was built on the original data to investigate which variables have an effect on Cp_{tot} of the tree species. The PLS model was validated by a segmented cross-validation, where 12 segments were used, and the segmentation was done by Venetian blinds in accordance with the Cp_{tot} values, in order to minimize extrapolation for all of the segments. Thus it was possible to plot the final regression coefficients with their corresponding uncertainties according to the Jack-knife scheme (Efron, 1982; Martens and Martens, 2000).

Results and discussion

Particle deposition and species differences in leaf characteristics

Coniferous Scots pine showed the highest particle capture efficiency of the tested tree species with a Cp_{tot} significantly greater than the broadleaved species (Fig. 1). This is in line with previous studies with coniferous species such as Corsican pine, Douglas fir and cypress (Beckett et al., 2000; Freer-Smith et al., 2004; Freer-Smith et al., 2005). Pubescent birch was the most efficient particle collector of the broadleaved species (statistically indicative) whereas the Cp_{tot}s of silver birch and lime were similar (Fig. 1). The Cp_{tot} values of Scots pine were in the upper range compared to other coniferous species (Table 2). The broadleaved species in this study were in the mid-range of the previously reported values at a similar wind velocity (Table 2). In terms of Vg_{tot} our results were in line with previous studies (Table 2). Cp_{tot} and Vg_{tot} values are sensitive to changes, e.g., in particle size. Thus, care is needed to compare results of different studies (Belot and Gauthier, 1975; Hinds, 1999; Beckett et al., 2000; Freer-Smith et al., 2004; Räsänen et al., 2012).

The studied tree species clustered clearly to species specific groups when plotted in PCA (Fig. 2a. A PCA loading plot (Fig. 2b) of the measured variables (Tables 3 and 4) shows the characteristics that these clusters have. Scots pine was described by a waxy, non-wettable surface (high contact angle) on the convex side of the needle whereas stomatal conductance and transpiration were low (Fig. 2b) and there were no trichomes (Fig. 3j-l). It should also be noted that the unit leaf area of the Scots pine was 20 to 40 times smaller than the broadleaved species (Table 3) and Cp_{tot} was 2 to 5 times higher (Fig. 1). The greater particle capture efficiency on smaller leaves has been related to tree architecture (Beckett et al., 2000; Freer-Smith et al., 2004). Silver birch was the most different to Scots pine, having the highest amount of trichomes (Fig. 2b and Fig 3d, e) and also high stomatal conductance and transpiration (Fig. 2b). Pubescent birch was the most hairy for both lower and upper sides of the leaf (Fig. 2b, 3a, b), had the widest stomata (Fig. 2b, 3 c) and low stomatal density (Fig. 2b). Lime was described by large unit leaf area, small stomata, high stomatal density and low amount of hairs (Fig. 2b and Fig. 3g-i). For the broadleaved trees, pubescent birch and silver birch had two times smaller leaves than lime (Table 3), but this did not reflect in the Cp_{tot}s (Fig. 1). Trees' single-sided leaf area versus ground surface area, referred to as leaf area index (LAI, m^2 m^{-2}), have been reported to range from 3 to over 10 for coniferous species and from 4 to 7 for broadleaved species. This further emphasizes the importance of evergreen coniferous species in particle capture (Gower and Norman, 1991; Bréda, 2003), both as forest trees and when planted in built-up areas.

Fine particles (Fig. 3 j-l) were equally as common on Scots pine and silver birch stomata. In both species, the numbers of particles on stomata were significantly higher ($p < 0.05$, ANOVA, Dunnett T3) than on the stomata of pubescent birch and lime, which had almost no particles (Table 3). Thus, equal amounts of particles were found on the stomata of the trees with the highest (Scots pine) and lowest (silver birch) Cp_{tot}, which indicates that factors other than stomatal conductance and transpiration have an important effect on particle deposition on the stoma area.

Characteristics that have effects on fine particle capture efficiency of the tested trees were investigated in more detail with a PLS model ($r = 0.71$, Root-Mean-Squared-Error-of-Cross-Validation (RMSECV) = 0.057) built with the measured variables. The model, with all species included, indicated that small unit leaf area and low stomatal density increases Cp_{tot} (data not shown). The result is explained by superior particle capture efficiency of Scots pine, which had small unit leaf area. Scots pine was also described by a waxy surface (Fig. 3 k, l) and low stomatal conductance and transpiration, all of which have been suggested to increase particle capture (Beckett et al., 2000; Räsänen et al., 2012; Sawidis, 2012). The characteristics of Scots pine differed to such a degree from the broadleaved species that another PLS-model was built omitting Scots pine to get more information regarding how the measured variables influence Cp_{tot} values. The PLS model for broadleaved species ($r = 0.58$, RMSECV = 0.02) showed higher Cp_{tot} values with a greater amount of hairs on both sides of the leaf, higher values of stomatal conductance and transpiration and larger contact angle on the lower side of the leaf (Fig. 4). Hairs have been suggested to explain particle deposition efficiency of certain species (Little, 1977; Beckett et al., 2000; Baraldi et al., 2011), but this is the first study where the significance of hair density in efficiency of $PM_{2.5}$ capture has been confirmed by a quantitative method. Cp_{tot} was also increased with low amounts of trichomes on both sides of the leaf and low stomatal density (Fig. 4). The negative effect of trichomes on Cp_{tot} can be due to the fact that the species having low amounts of trichomes tend to be efficient at particle capture due to other variables (e.g hairs, Table 3). Furthermore, the smooth structure of trichomes is not likely to enhance particle capture. Low wettability of the leaf surface (large contact angle) can also increase particle deposition on broadleaved trees, similar to the situation with waxy coniferous species (Burkhardt et al., 1995). Other surface characteristics, such as hairs, can also affect contact angles.

Cp_{tot} increased with low stomatal density and high stomatal conductance, which indicates that the activity of stomata increases particle deposition on broadleaved species. This is opposed to findings with coniferous species where particle deposition decreased with increasing transpiration (Räsänen et al., 2012). The markedly higher activity of broadleaf stomata can also make particles more deliquescent, which can increase deposition rate (Burkhardt et al., 2001). Transpiration of water through stomata cools the surface and can also increase fine particle deposition by thermophoresis (Hinds, 1999). The remaining variables, leaf area, contact angle upper side and soil moisture (see Fig. 4) had non-significant contributions to the regression model.

Effects of reduced water availability

Our earlier study with Norway spruce demonstrated that moderate soil drought stress increased particle collection efficiency (Räsänen et al., 2012) and a similar trend can also be seen here with Scots pine (Fig. 1). However, in broadleaved species the Cp_{tot} did not respond to reduced water availability. PCA did not reveal any effects of reduced water availability on leaf structure or stomatal functioning when species were separated (Fig. 2a). However, when the effects of watering treatment were studied in more detail, a few differences were noted. Lowered water availability reduced the unit leaf area (ULA) of silver birch and pubescent birch. ULA (± SE) were 47.4 ± 3.4 cm^2 and 34.3 ± 2.8 cm^2 for silver birch control and drought treated saplings, respectively, and 54.1 ± 3.6 cm^2 and 39.9 ± 1.4 cm^2 for pubescent birch control and drought treated saplings respectively. The differences were statistically significant for both silver birch and pubescent birch ($p = 0.014$ and $p = 0.004$, respectively, Independent Samples T-test). Moreover, stomatal conductance and transpiration of Scots pine was 66% and 60% higher, respectively, in well watered saplings compared to their drought treated counterparts (Table 4). A trend was observed for a greater Cp_{tot} of drought treated Scots pine saplings compared to well watered ones. Differences in the wax layer can alter particle deposition on surfaces of conifer needles (Burkhardt et al., 1995), but this was not seen in our study of Scots pine, with similarly shaped waxes (median values of 2, range 1-2) on plants subjected to both watering treatments ($p>0.05$, Wilcoxon). Stomatal conductance of the drought-treated Scots pine, silver birch and lime and transpiration of drought-treated Scots pine decreased during the test run (Table 4), which indicates that the drought treatment has an effect on stoma function at a wind velocity of 3 m s^{-1}.

Conclusions

Leaf size affects Cp_{tot} of trees the most when coniferous and broadleaved species are compared. Among the broadleaved species hairiness of the leaf, low stomatal density and low leaf wettability (large contact angle of water droplet) increase Cp_{tot}. Moderate soil drought tended to increase particle capture efficiency of Scots pine, but did not have an effect on broadleaved species. Furthermore, we propose that the total surface area of needles/leaves should be used in capture efficiency and deposition velocity calculations because the entire surface is taking part in particle deposition and the results of broadleaved and coniferous species are more comparable.

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TABLES

Table 1. Soil moisture values (%, mean ± SE) of tested tree species in well watered (control) group and reduced water (drought) group (n = 6, except n = 9 for lime control and n = 3 for lime drought) before exposure in the wind tunnel.

	S. pine	P. birch	Lime	S. birch
Control	52 ± 2	39 ± 4	58 ± 1	52 ± 4
Drought	32 ± 6	12 ± 1	35 ± 4	29 ± 4

Table 2. Particle capture efficiency ± SE (Cp, %, n = 12) and deposition velocity ± SE (Vg_{tot}, cm s^{-1}, n = 12) values of tree species of this study compared to other studies conducted with a wind velocity of 3 m s^{-1} and particle size of $PM_{2.5}$. Cp and Vg values of Freer-Smith et al. (2004) and Beckett et al. (2000) have been converted to match our results (i.e. total needle/leaf area is used instead of projected area) by dividing the original results by 2 for broadleaved species and by 2.6 for coniferous species. Cp and Vg values estimated from the graph of Belot (1975) were multiplied by 6 for broadleaved species and by 5 for coniferous species.

	Cp	Vg	Reference
Broadleaved trees			
Acer campestre	0.01	0.04	Beckett et al. (2000)
Acer pseudo-platanus	0.01	0.02	Freer-Smith et al. (2004)
Alnus glutinosa	0.02	0.06	Freer-Smith et al. (2004)
Betula pendula	0.043 ± 0.005	0.13 ± 0.01	This study
Betula pubescens	0.083 ± 0.01	0.25 ± 0.04	This study
Cupressocyparis leylandii	0.13	0.38	Beckett et al. (2000)
Eucalyptus globulus	0.003	0.009	Freer-Smith et al. (2004)
Ficus nitida	0.01	0.02	Freer-Smith et al. (2004)
Fraxinus excelsior	0.03	0.089	Freer-Smith et al. (2004)
Populus deltoids x trichocarpa	0.02	0.06	Beckett et al. (2000)
Quercus petraea	0.14	0.42	Freer-Smith et al. (2004)
Quercus sessiliflora	0.06	0.19	Belot and Gauthier
Sorbus intermedia	0.07	0.20	Beckett et al. (2000)
Tilia vulgaris	0.047 ± 0.003	0.15 ± 0.01	This study
Conifers			
Picea abies	0.06	0.17	Räsänen et al. (2012)
Pinus nigra	0.15	0.44	Beckett et al. (2000)
Pinus sylvestris	0.21 ± 0.02	0.65 ± 0.06	This study
	0.15	0.46	Belot and Gauthier
Pseudotsuga menziesii	0.16	0.49	Freer-Smith et al. (2004)

Table 3. Mean (±SE) of measured variables without watering treatment classification (n=12). Variables that were not found are indicated with n.d.

	Scots pine	Pubescent birch	Lime	Silver birch
Stomatal density (mm^{-2})	92.2 ± 4.5	111.1 ± 5.8	260 ± 13.1	174.6 ± 13.0
Stoma diameter (µm)	22.8 ± 0.8	31.0 ± 0.9	12.1 ± 0.4	24.0 ± 0.9
Stomata with particles (%)	17.5 ± 4.4	1.8 ± 0.9	2.5 ± 1.1	20.6 ± 4.9
Unit leaf area (cm^2)	2.0 ± 0.1	47.0 ± 2.8	98.7 ± 8.4	40.8 ± 2.9
Contact angle				
upper side (º)	80.2 ± 2.4	79.5 ± 5.5	36.3 ± 3.3	40.5 ± 4.1
lower side (º)	68.9 ± 4.5	86.8 ± 4.0	85.1 ± 2.3	68.0 ± 3.3
Trichomes (mm^{-2})				
upper side	n.d.	0.5 ± 0.3	0.03 ± 0.1	4.3 ± 1.6
lower side	n.d.	1.0 ± 1.2	0.03 ± 0.1	6.4 ± 3.9
Hairiness (mm^{-2})				
upper side	n.d.	14.0 ± 6.7	1.1 ± 0.7	1.3 ± 1.5
lower side	n.d.	13.9 ± 5.4	3.5 ± 2.5	1.3 ± 2.7

Table 4. Stomatal conductance and transpiration mean values (± SE, n = 6, except n = 9 for lime control and n = 3 for lime drought) of four tree species in wind tunnel experiments. Differences between watering groups (columns) within the species were tested with Independent-Samples T-test and differences between the start and end of the experiment (lines) with Paired-Samples T-test.

	Stomatal conductance (cm s^{-1})		Transpiration (µg cm^{-2} s^{-1})	
	Start	End	Start	End
Scots pine				
Control	0.15 ± 0.016	0.15 ± 0.035	1.63 ± 0.21	1.48 ± 0.41
Drought	0.12 ± 0.025	0.05 ± 0.010[a,Δ]	1.33 ± 0.29	0.59 ± 0.19[b,Δ]
Pubescent birch				
Control	1.43 ± 0.73	1.15 ± 0.91	13.51 ± 6.57	10.15 ± 7.23
Drought	0.42 ± 0.19	0.53 ± 0.26	5.20 ± 2.31	6.88 ± 3.31
Lime				
Control	0.61 ± 0.27	0.80 ± 0.35	8.29 ± 3.69	10.89 ± 4.54
Drought	1.47 ± 0.66	1.26 ± 0.69[Δ]	17.51 ± 8.00	15.54 ± 8.37
Silver birch				
Control	1.82 ± 0.34	1.21 ± 0.36	16.53 ± 3.23	16.02 ± 3.79
Drought	1.66 ± 0.52	0.88 ± 0.38[Δ]	12.12 ± 5.20	15.88 ± 3.31

[a] $p < 0.05$, Independent-Samples T-test

[b] $p < 0.1$, Independent-Samples T-test

[Δ] $p < 0.05$, Paired-Samples T-test

FIGURES

Fig. 1. Fine particle capture efficiency (Cp_{tot}% ± SE, n = 6, except n = 9 for lime control and n = 3 for lime drought) of tested tree species for well watered control treatment (white bars) and reduced water treatment (grey bars).

Fig. 2. PCA analysis of the tree species with 11 species dependent variables. A) Score plot of the tested tree species with two different watering treatments. B) Corresponding loading plot, with the degree of explained variables shown in grey scale. Black indicates well explained variables, and white (contact angle lower) indicates poorly explained variables. Lower refers to lower side of the leaf and upper to upper side of the leaf, and straight and convex edges of the pine needle.

Fig. 3. Scanning electron microscope pictures of pubescent birch (a-c), silver birch (d-f), lime (g-i) and Scots pine (j-l). Pictures a, d and g are from the upper side of the leaf and b, e and h are from lower side of the leaf. Stomata are shown in c, f, i, k and l. Note thick coverage of tubular waxes on epistomatal area of pine needles in k, l. Symbols indicate examples of hair (arrow), trichome (circle), stoma (triangle) and salt particles (sharp line).

Fig. 4. Regression coefficient of PLS model for the factors affecting Cp_{tot} of broadleaved species. The vertical lines indicate +/- 2 standard deviations in the regression coefficients. Thus if one of these lines crosses zero, the variable does not have a significant contribution in explaining the Cp_{tot}.