FOLIAGE AND STEM DRAG: COMPARISON BETWEEN FOUR RIPARIAN SPECIES

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Abstract

This paper investigates the flow resistance of foliated trees by partitioning the total drag into two components: foliage drag and stem drag. The drag forces of four foliated and defoliated Common Osier (*Salix viminalis*), hybrid Crack Willow (*Salix x rubens*), Common Alder (*Alnus glutinosa*) and Silver Birch (*Betula pendula*) were directly measured. The foliage drag was determined by subtracting the stem drag from the total drag. The relationship between the drag and readily measurable plant properties was analyzed for each species. The stems were characterized using four properties: dry mass, wet mass, frontal bent stem area, and volume. The stem drag per each of these properties was similar for all four species. Therefore, the stem drag of leafless twigs of these species can be estimated using the same relationships. The foliage was characterized using three properties: dry mass, wet mass, and one-sided leaf area. For *Alnus glutinosa*, *Betula pendula* and *Salix x rubens*, the foliage drag per any of the three properties was 1.5-3 times higher compared to *Salix viminalis*. The most notable differences between the species were observed in the foliage drag per leaf dry mass. The foliage drag per leaf area was similar for *Alnus glutinosa*, *Betula pendula* and *Salix x rubens*, indicating that the same relationships can be applied for predicting the foliage drag of these species. The findings implied that the between-species variability in the flow resistance of foliated twigs resulted mostly from the differences in the leaf properties rather than the stem properties.

Introduction

In addition to their ecological significance for the riparian and floodplain ecosystems, trees and bushes can be used to control erosion on channel banks or to trap suspended sediment and nutrients on floodplains and constructed wetlands. Many design and management purposes require reliable estimation of the flow resistance of foliated trees, preferably on the basis of physically sound and readily obtainable properties of the plants. Flow resistance of deciduous trees has been examined in many studies (e.g. Järvelä, 2004; Vollsinger et al., 2005; Wilson et al., 2010). However, the variation in the plant properties used for parameterization of the flow resistance and drag, such as frontal projected area, one-sided leaf area, crown mass and leaf mass, makes it difficult to compare the different studies. Therefore, further studies examining the suitability of various plant parameters for the estimation of flow resistance are needed. As flow resistance formulations based on certain parameters may be more species-specific than others, parameters allowing for the resistance formulations to be applied not only to one but to several deciduous foliated species would be attractive for the practical applications.

The complexity of predicting the drag of foliated trees is related to the fact that different plant parts, most importantly leaves and stems, obviously have very different mechanical properties. For instance, a higher leaf-area-to-stem-area ratio A_L/A_S decreases the total drag per leaf area F/A_L for foliated Black Poplar (*Populus nigra*) twigs (Västilä et al., 2011). Further, F/A_L of the Black Poplars was only half of that for hybrid willows (*Salix triandra x viminalis*) of the same length examined by Järvelä (2006). However, it is not clear to which extent the observed dissimilarities were caused by the differences in the material properties of leaves and stem between the two species, and to which extent by the different A_L/A_S ratios between the species (Västilä et al., 2011). As a whole, partitioning the total drag F of foliated species into the components of stem drag F_S and foliage drag F_L may help to elucidate the flow resistance of foliated trees.

The key mechanisms and plant properties governing the flow resistance of foliated trees can be understood by examining the plants at various relevant scales. At least three important scales can be distinguished: whole foliated trees, the foliage or stem, and leaf or leaf cluster. Investigations at the scale of whole foliated trees have revealed the importance of the reconfiguration of the plants under flow and the associated deviation from the squared drag-velocity relationship valid for rigid objects (e.g. Järvelä, 2004; Vollsinger et al., 2005; Wilson et al., 2010). At the other end of the scale range, Vogel (1989) and Albayrak et al. (2012) have investigated the drag for single leaves and leaf clusters with the petioles positioned in a downstream orientation. For instance, Vogel (1989) reports a larger drag per leaf area for leaves with acute bases and short petioles as opposed to leaves with lobed bases and long petioles. Studies with artificial leaves have shown that the streamlined shape of elliptical leaves results in a slightly lower drag per leaf area compared to elongated, rectangular leaves while pinnate leaves have a substantially higher drag than the two other shapes (Albayrak et al., 2012). Further, for artificial leaves of a selected shape, a higher flexural rigidity increases the drag. Since leaves in the natural trees are not attached to the stem with the petioles oriented downstream, estimating the foliage drag F_L of natural trees requires investigations with specimens having a natural orientation of the leaves in relation to the stem. This can be considered as the foliage scale, an intermediate scale between whole trees and single leaves. On the other hand, the stem drag F_S of defoliated trees is better understood than the drag of foliated trees, and F_S is usually expressed with the drag coefficient C_D=C_D(Re). C_D of natural defoliated trees is approximately 1−2 for stem Reynolds numbers of 1000−10000 (Järvelä, 2002; Armanini et al., 2005; Wunder et al., 2011). However, the stem drag may vary for different species due to e.g. differences in the roughness of the stem or in the flexibility of the stem.

This paper investigates the differences and similarities in the stem and foliage drag of four common riparian tree species. The stem and foliage drag are examined in relation to readily measurable plant properties: the stems are characterized using four properties (dry mass, wet mass, frontal bent stem area, and volume), and the foliage with three properties (dry mass, wet mass, and one-sided area of the leaves). The applicability of the obtained stem and foliage drag relationships to the different species is analyzed.

Methods

Flume experiments

Experiments were performed in the 32 m long and 0.6 m wide tilting laboratory flume with four tree species: Common Osier (*Salix viminalis*), hybrid Crack Willow (*Salix x rubens*), Common Alder (*Alnus glutinosa*) and Silver Birch (*Betula pendula*) (Figure 1). The tested specimens were 23 cm tall tips of branches, in this paper referred to as twigs, collected from saplings and mature trees growing in Braunschweig, Germany. For each species, drag forces of four specimens were simultaneously measured with drag force sensors (DFS) described in detail by Schoneboom et al. (2008). The DFS were located under the bottom of the flume, and the twigs were attached to them in an upright position with the main stem bent towards downstream in the standing water (Figure 2). The four DFS were arranged to a rectangular pattern that provided the least disturbed approach flow conditions for each of the four specimens. The longitudinal distance of 1.2 m between the plants minimized the flow disturbance of the upstream plants on the downstream plants while the lateral distance of 0.3 m ensured that the adjacent plants did not interfere with each other.

The experiments consisted of measuring the drag forces F of the foliated specimens at the target mean velocities u of 0.2, 0.5 and 0.8 m/s. The leaves were then removed and the same plants were tested in the defoliated condition to obtain the stem drag F_S. The defoliated plants, consisting of the main stem and the side-twigs, are hereafter referred to as stems. For each specimen, the foliage drag F_L at each velocity was determined as

$$F_L = F - F_S \tag{1}$$

The drag forces were recorded at the sampling rate of 200 Hz for three periods of 60 s as pre-tests showed that this was a sufficient measurement period to reach a reproducible mean value. The experiments were conducted under steady uniform flow with the plants just submerged, which was obtained by adjusting the water depth by a tailgate located 9 m downstream from the plants. The discharge was measured by an inductive flow meter and controlled by a valve to achieve the target velocities. Mean velocity u was determined with the continuity equation neglecting the vegetation volume.

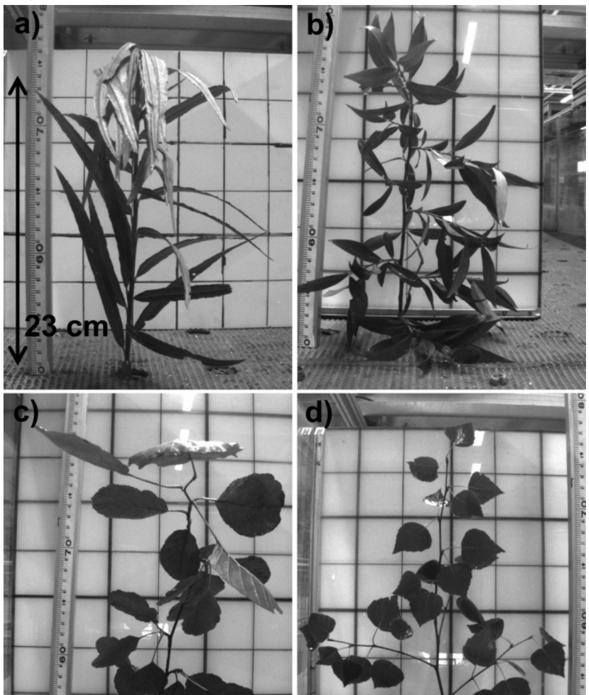

Figure 1. Examples of the examined 23 cm tall twigs of Common Osier (*Salix viminalis*, a), hybrid Crack Willow (*Salix x rubens*, b), Common Alder (*Alnus glutinosa*, c) and Silver Birch (*Betula pendula*, d).

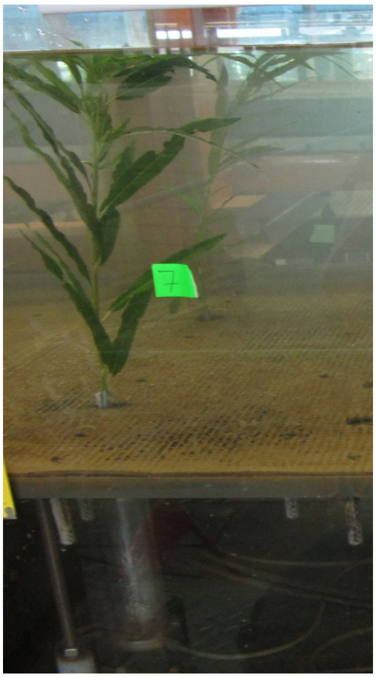

Figure 2. A *Salix viminalis* specimen attached to the drag force sensor located below the flume bottom.

Plant properties

After the experiments, four properties of the stem and three properties of the foliage were determined (Table 1). The diameter d of the main stem was measured at the relative heights of 0, 1/4, 2/4 and 3/4 with a caliper. The length l of the main stem in each quartile of relative height was determined to account for the bent stature that some specimens had (Figure 3). For each side-twig, the mid-diameter and the length were measured. The stem volume was computed from these measurements as $V_S=\sum\pi(d/2)^2l$, and the frontal bent stem area as $A_S=\sum dl$, the two parameters comprising both the main stem and side-twigs. After gently drying the water on their surfaces with paper towels, the leaves and stems were weighted to obtain the leaf wet mass $m_{L,W}$ and the stem wet mass $m_{S,W}$. The leaves were subsequently scanned, and the one-sided leaf areas A_L were determined from the scanned images with image analysis software. In this paper, leaf area refers to the one-sided leaf area. Finally, the leaves and stems were dried in an oven at 105 °C for 24 h for the determination of the leaf dry mass $m_{L,D}$ and the stem dry mass $m_{S,D}$. The leaf areas and frontal bent stem areas of each species are presented in Table 2.

Table 1. The examined stem and foliage properties.

Stem property	**Foliage property**
Stem wet mass, $m_{S,W}$	Leaf wet mass, $m_{L,W}$
Stem dry mass, $m_{S,D}$	Leaf dry mass, $m_{L,D}$
Frontal bent stem area, A_S	One-sided leaf area, A_L
Stem volume, V_S	-

Table 2. One-sided leaf areas A_L and frontal bent stem areas A_S of the four species. Means ± 1 standard error.

Species	Stem area A_S (cm^2)	Leaf area A_L (cm^2)
Common Alder (*Alnus glutinosa*)	11±1.0	350±41
Silver Birch (*Betula pendula*)	8±0.7	200±16
Common Osier (*Salix viminalis*)	10±0.9	370±53
hybrid Crack Willow (*Salix x rubens*)	13±1.4	320±61

Analysis

Stem and foliage drag relationships were formed for each species by dividing the stem drag, or the foliage drag, by the various stem, or foliage, properties, respectively. The velocities for each species slightly differed from the target velocities. However, as the differences in velocity between the species were lower than 1.6% at each target velocity, the measured data were analyzed without adjusting for the velocity. The results are reported as mean, and the 95% confidence intervals are shown in figures. Differences between the species were tested with the analysis of variance (ANOVA) separately for each of the three velocities. In the ANOVA, the Welch correction was applied as the variances were unequal. To determine which species differed from each other, significant ANOVAs were followed with *post-hoc* Dunnett's T3 tests allowing for unequal variances. A probability of $p<0.05$ was considered significant. The p-values at the three velocities were grouped into one p-value if all of them were either significant or nonsignificant, and are therefore reported as "higher than" ($p>x$) for the nonsignificant p-values and as "lower than" ($p<x$) for the significant p-values. Statistical analyses were conducted with SPSS Statistics 20.0.0.

Results

Stem drag relationships

The stem drag relationships between the measured stem drag F_S and the four stem properties are shown in Figure 3. The mean values of the stem drag relationships for the four species fell close to each other, and the relationship between F_S and u was approximately squared for each species. The species did not differ in the stem drag per stem wet mass $F_S/m_{S,W}$ ($p>0.24$, Figure 3a), or in the stem drag per stem dry mass $F_S/m_{S,D}$ ($p>0.13$, Figure 3b). Neither were differences found among the species in the stem drag per stem area F_S/A_S ($p>0.46$, Figure 3c) or in the stem drag per stem volume F_S/V_S ($p>0.43$, Figure 3d). These results showed that the four species had similar stem drag at the twig scale. This finding is in agreement with Tanaka et al.

(2011), who found that the between-species variation in stem drag, expressed as C_D, is small for 8 cm thick tree trunks of two species differing in surface roughness.

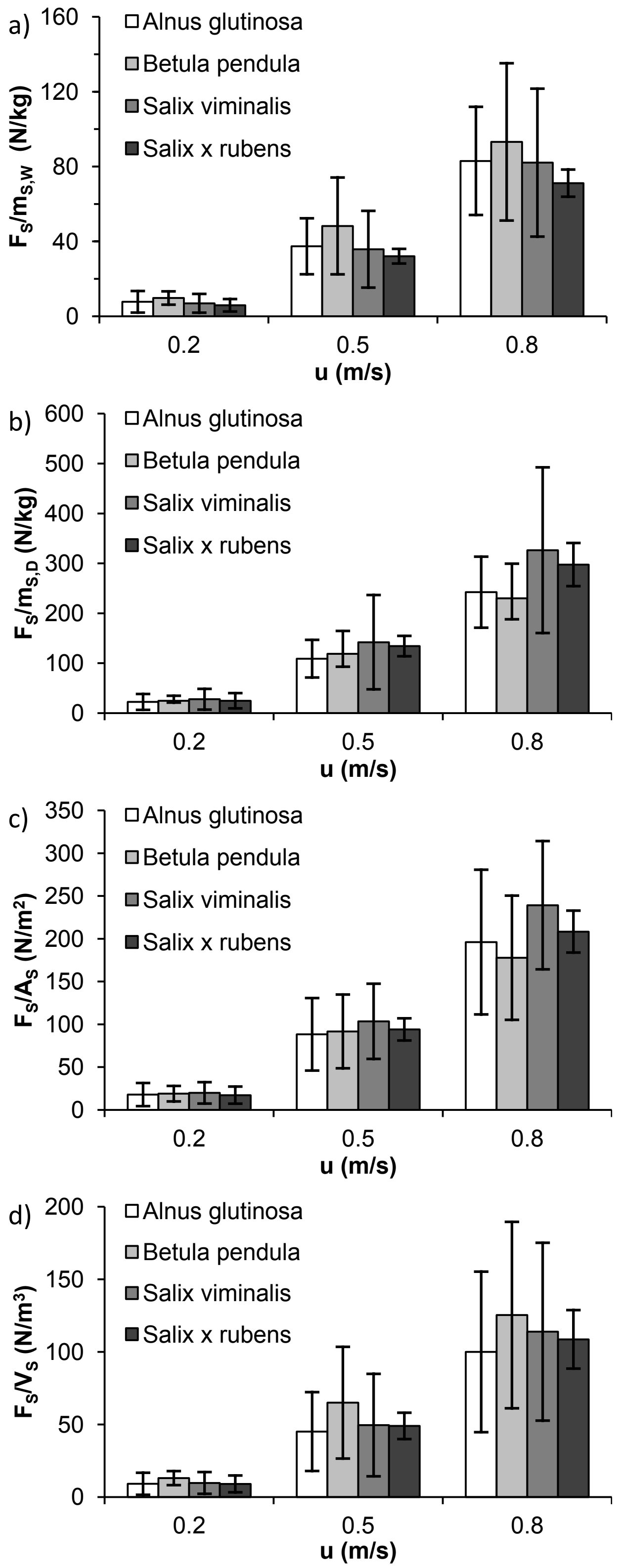

Figure 3. Stem drag per stem wet mass (a), stem dry mass (b), stem area (c), and stem volume (d) for the four species investigated at three velocities. Means and the 95% confidence intervals are shown.

The mean values of the stem drag relationships were fairly equal for all four species, but the large confidence intervals in Figure 3 illustrate the notable variability in the stem drag within each species. The most extensive confidence intervals relative to the mean values were derived at the lowest velocity, which results from the fact that the measured forces at 0.2 m/s (0.01-0.04 N) were only slightly higher than the error of the measurement system (±0.01 N according to Schoneboom et al., 2008). Excluding the results at 0.2 m/s, the coefficient of variation (standard deviation divided by the mean) was similar for $F_S/m_{S,D}$, $F_S/m_{S,W}$ and F_S/A_S. However, since the mean measurement error of A_S (estimated at ~10%) was over an order of magnitude larger than that of $m_{S,D}$ or $m_{S,W}$ (<1%), a greater share of the variability in A_S was assumed to originate from measurement errors. V_S was the least accurate predictor of stem drag, but it also had the highest measurement error.

The large confidence intervals are partly explained by the inherent variability of the natural plants. For instance, one specimen of *Salix viminalis* demonstrated notably lower stem drag relationships than the three other specimens. This particular specimen was characterized by a bent stature (Figure 4a) while the other specimens had a more upright stature (Figure 4b). Since form drag dominates over skin friction for such riparian species (e.g. Nikora, 2009), specimens with a bent stature are expected to have a lower drag in relation to the examined stem parameters than those with an upright stature. Similarly, a notably larger drag was obtained for a specimen of *Alnus glutinosa* having a more upright stature than the remaining three specimens. In the future, we will analyze whether the photographed frontal projected areas of the stems provide a more accurate predictor for the stem drag than the parameters investigated within this paper.

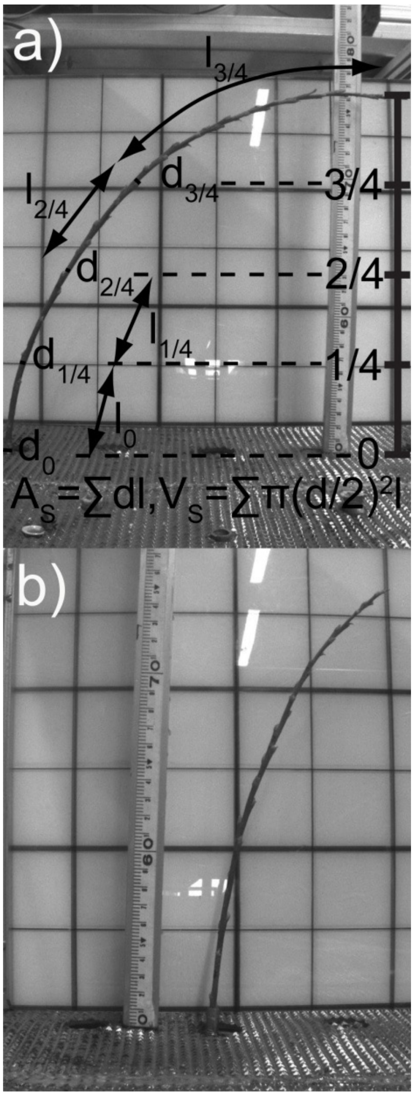

Figure 4. A *Salix viminalis* specimen having a bent stature (a), and a specimen having a more upright stature (b). Photographs were taken in still air. Figure (a) also shows the determination of the frontal bent stem area A_S and stem volume V_S.

Foliage drag relationships

The foliage drag relationships between the computed foliage drag F_L and the three foliage properties are shown in Figure 5. The foliage drag increased approximately linearly with the velocity. Differences among the four species were found in the foliage drag per leaf wet mass $F_L/m_{L,W}$ ($p<0.001$), in the foliage drag per leaf dry mass $F_L/m_{L,D}$ ($p<0.001$), and in the foliage drag per leaf area F_L/A_L ($p<0.009$). The *post-hoc* Dunnett's T3 tests revealed many similarities in the foliage drag relationships among *Alnus glutinosa*, *Betula pendula* and *Salix x rubens* while all three examined relationships had particularly low values for *Salix viminalis*. For *Alnus glutinosa*, *Betula pendula* and *Salix x rubens*, the values of the three foliage drag relationships were about 1.5- to over 3-fold compared to those of *Salix viminalis*.

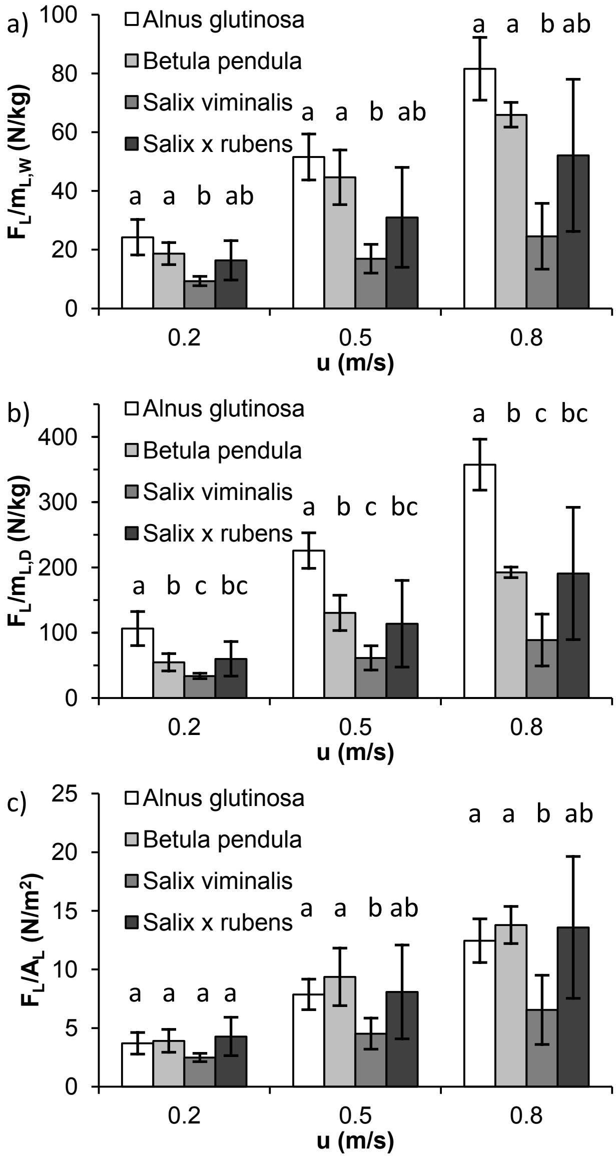

Figure 5. Foliage drag per leaf wet mass (a), leaf dry mass (b), and leaf area (c) for the four species investigated at three velocities. Means and the 95% confidence intervals are shown. The letters a, b and c denote species that significantly differ from each other ($p<0.05$).

The values of the three foliage drag relationships were similar for *Betula pendula* and *Salix x rubens* (Figure 5). Further, $F_L/m_{L,W}$ and F_L/A_L of *Alnus glutinosa* were similar to those of *Betula pendula* and *Salix x rubens* (Figures 5a and c) whereas $F_L/m_{L,D}$ of *Alnus glutinosa* was significantly higher than that for the two species (Figure 5b). The greater differences in $F_L/m_{L,D}$ between *Alnus glutinosa* and the other two species compared to $F_L/m_{L,W}$ were associated with the fact that the ratio of the leaf dry mass to leaf wet mass differed between the species, with the lowest value obtained for *Alnus glutinosa* and the highest for *Betula pendula*. *Salix viminalis* had significantly lower $F_L/m_{L,W}$ and $F_L/m_{L,D}$ than *Alnus glutinosa* or *Betula pendula* (Figure

5a and b). *Salix viminalis* also had a lower F_L/A_L than the two species at the velocities of 0.5 m/s and 0.8 m/s while the p-values at 0.2 m/s ($0.055<p<0.075$) were low but nonsignificant (Figure 5c). The foliage drag relationships did not show statistically significant differences between *Salix viminalis* and *Salix x rubens* due to the extensive confidence intervals derived for *Salix x rubens*.

The most similar foliage drag relationships among the species were obtained when leaf area A_L was used as the foliage parameter. This finding was physically sound since drag is expected to be more directly related to the area exposed to flow, both via form drag and skin friction, than to mass. Therefore, using leaf area as the foliage parameter allows the same foliage drag relationships to be applied not only to one but to several foliated tree species. By contrast, foliage drag relationships based on leaf dry mass $m_{L,D}$ and leaf wet mass $m_{L,W}$ were more species-specific.

The obtained differences in the foliage drag between the species were assumed to be caused by differences in either the properties of the leaves or in the original stature of the leaves with respect to the main flow direction. Irrespective of the employed foliage parameter, *Salix viminalis* was notably more efficient in minimizing the foliage drag than the three other species. Although the differences were not statistically significant, the mean values of the drag relationships were approximately double for *Salix x rubens* compared to those of *Salix viminalis* despite of the fact that the species belong to the same genus. This finding was associated with the observation that the leaves of *Salix viminalis* seemed to orient themselves in the main flow direction more easily than those of *Salix x rubens*, suggesting that the mechanical properties of the leaf blades or petioles differed between the two species. Future analysis of the recorded projected areas under flow will give more insight about the reconfiguration properties of the four species. Further, as elliptical and rectangular leaves with serrated margins have on average 12% higher drag per leaf area compared to leaves with smooth margins (Albayrak et al., 2011), the smooth margins of the *Salix viminalis* leaves can be expected to have a decreasing effect on foliage drag as opposed to the moderately serrated margins of the *Betula pendula* and *Alnus glutinosa* leaves.

Conclusions

Investigations with four foliated and defoliated deciduous species revealed that the species had similar stem drag but differed in foliage drag. The stem drag per each of the examined stem parameters (dry mass $m_{S,D}$, wet mass $m_{S,W}$, frontal bent stem area A_S, and stem volume V_S) was similar for all four species. Therefore, the stem drag of leafless twigs of these species can be estimated using the same relationships. Of the three explored foliage parameters, the foliage drag relationship based on leaf area had the best applicability for various species: the foliage drag per leaf area A_L was similar for *Alnus glutinosa*, *Betula pendula* and *Salix x rubens* whereas the foliage drag per leaf dry mass $m_{L,D}$ and leaf wet mass $m_{L,W}$ was more species-specific. The findings suggested that the between-species differences in the drag of foliated twigs resulted more from differences in the leaf properties than in the stem properties.

Acknowledgements

The support of Dr.-Ing. Jochen Aberle and the technicians at the Leichtweiß-Institute of the TU Braunschweig is acknowledged. The authors are grateful for the financial support from the Academy of Finland and Maa- ja vesitekniikan tuki ry.

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