Characteristic reference areas for estimating flow resistance of natural foliated vegetation

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Abstract: Reliable estimation of vegetative flow resistance calls for physically sound and readily measurable plant properties. Laboratory flume investigations were conducted to examine four reference area properties in relation to the drag, reconfiguration, and flow resistance of foliated Black Poplar twigs. The experiments were novel in that three characteristic reference areas (leaf area $A_L$, frontal projected area under flow $A_P$, and still-air frontal projected area $A_0$) as well as the foliage–stem reference area ratio ($A_L/A_S$) were evaluated. The drag forces were simultaneously measured for up to eight specimens in a plant stand at both partly and just submerged conditions. Due to the high $A_L/A_S$ of the twigs, leaves contributed 74-98% of the total drag at mean velocities of 0.1-0.9 m/s. Both the partly and just submerged poplars had similar $A_P$ and drag per characteristic reference area. Thus, the derived parameter values could be used to estimate the friction factors of the poplar stands at low to just submerged conditions, with each of the three characteristic reference areas providing satisfactory estimates. The flow resistance estimation with $A_L$ could be further improved by using $A_L/A_S$ as a secondary area parameter to take into account the share of the stem to the total drag. Comparison to literature data on other deciduous species suggested that the foliage–stem reference area ratio was an essential property for explaining the between-species variation in $A_P$ and flow resistance per $A_L$.

Keywords: vegetation, foliage, drag force, flow resistance, reconfiguration, characteristic reference area

1. Introduction

Vegetation is a fundamental component of floodplain and riparian ecosystems, and vegetative flow resistance needs to be estimated for many management and restoration purposes. Approaches based on physically sound and readily measurable properties of vegetation are expected to provide the most reliable and objective estimates. Of the different vegetation types, the flow resistance of foliated deciduous trees and shrubs is particularly difficult to estimate due to the limited understanding of the most suitable parameterization of these plants, applicability of the same parameter values
Deciduous species growing on floodplains and channel banks include for instance poplars (*Populus* spp.) and willows (*Salix* spp.). In general, deciduous species can be characterized as bending plants of a high flexural rigidity, as opposed to tensile plants of a very low flexural rigidity (Nikora, 2010). Tensile plants, such as many macrophytes, follow the flow, and their flow resistance is thus mainly generated by viscous drag (e.g. Miler et al., 2012). By contrast, bending plants experience mainly form drag despite the significant reconfiguration of the different plant parts when exposed to flow. The classical approach (e.g. Hoerner, 1965) defines the drag force $F$ exerted on an object in a flow as

$$ F = \frac{1}{2} \rho C_D A_c u_c^2 $$

(1)

where $\rho$ is fluid density, $A_c$ is the characteristic reference area, and $u_c$ is the characteristic approach velocity.

$C_D = C_D(Re)$ is the drag coefficient of the object while $Re$ is the object’s Reynolds number ($Re = u_l l / \nu$ where $l$ is the characteristic length of the object and $\nu$ is the kinematic viscosity of the fluid). For rigid, non-streamlined objects, $C_D$ is fairly constant at the $Re$ range relevant for practical applications, and therefore $F \propto u_c^2$ (e.g. Hoerner, 1965). By contrast, the $F$–$u_c$ relationship is closer to linear for foliated trees which are able to reconfigure into a more hydrodynamically efficient shape with increasing velocity (e.g. Cullen, 2005; Wilson et al., 2010). Expressing the relationship between drag and velocity for a given object as $F \propto u_c^{2+b}$ allows characterizing the deviation from the expected squared relationship with the Vogel exponent $b$ (Vogel, 1994). For instance, $b=-1$ for objects experiencing a linear increase in drag with the velocity. The Vogel exponent is thus a measure of the reconfiguration, i.e. of how drag changes with velocity (de Langre, 2008; Nepf, 2012). Deciduous species achieve reconfiguration for instance by reducing their frontal projected area $A_P$ (e.g. Wunder et al., 2011) and by acquiring a more streamlined shape of the leaf clusters (Vogel, 1989) and of the entire plant. Although reconfiguration alters the $C_D$ values of flexible vegetation (e.g. Dittrich et al., 2012), a constant $C_D$ is often assumed in practical applications when drag is modeled with Eq. 1.

In hydraulic engineering, flow resistance needs to be considered at the reach scale, at which vegetation can be regarded as plant stands comprised of individual trees and bushes. Flow resistance is commonly expressed with resistance coefficients, including the Darcy-Weisbach friction factor $f$ or Manning’s $n$ which are related as $f = 8gR^{-1/3}n^2$

where $g$ is acceleration due to gravity and $R$ is hydraulic radius. The total resistance coefficient may be divided into separate coefficients for the main contributing factors according to the superposition principle (Yen, 2002). In vegetated flows, for instance, the total friction factor $f$ may be separated into the friction factors due to vegetation ($f'$) and bed friction ($f''$) as $f = f' + f''$. In analogy to bed friction, the vegetative friction factor $f''$ of a plant stand consisting of uniform vegetation elements can be determined from the average drag force of the individual elements ($\langle F \rangle$) as
where \( a_x \) and \( a_y \) are the longitudinal and lateral spacing of the elements and \( u_m \) is the mean velocity. To estimate \( f'' \) for a stand of foliated trees or shrubs, Järvelä (2004) developed a formulation that uses a constant, species-specific drag coefficient \( C_D \):

\[
f'' = 4C_D \frac{F}{LAI} \left( \frac{u_m}{u_x} \right)^x
\]  

where \( LAI \) is leaf area index, defined herein as the ratio of the one-sided leaf area (\( A_L \)) to the ground area (\( A_o \)). LAI, i.e. \( A_L/A_o \), thus represents the characteristic reference area of the vegetation (in this case \( A_L \)) per ground area. Eq. 3 considers reconfiguration through the species-specific vegetation parameter \( \chi \) (which is equivalent to the Vogel exponent \( b \), Aberle & Järvelä, 2013) and the term \( u_m/u_x \) where the mean velocity \( u_m \) is normalized with \( u_x \) that denotes the lowest velocity used in determining \( \chi \). Values of the species-specific parameters may be derived from flume or field experiments. Eq. 3 is suitable for just submerged flow conditions (i.e. \( h/H \approx 1 \), where \( h \) is water depth and \( H \) is deflected plant height), but its applicability may be extended to partly submerged conditions (\( h/H \leq 1 \)) by defining a scaling parameter for LAI (Järvelä, 2004).

Formulations of both vegetative drag (Eq. 1) and friction factor (Eq. 3) employ the characteristic reference area, which has been defined in different ways for natural foliated vegetation (see e.g. Aberle et al., 2010). While studies on the wind throw risk of trees typically use the still-air frontal projected area (\( A_o \)) or the frontal projected area under flow (\( A_f \)) as the reference area (Koizumi et al., 2010; Rudnicki et al., 2004; Vollsinger et al., 2005), analyses on the performance of \( A_f \) and \( A_o \) for trees in water flows are scarce (however, see Dittrich et al., 2012; Wunder et al., 2011). On the other hand, the one-sided leaf area (\( A_L \)) of Eq. 3 seems to be a physically sound reference area as foliage may generate half or more of the drag of deciduous saplings (Järvelä, 2002; Vollsinger et al., 2005). The various reference area definitions may be employed in the estimation of the vegetative friction factor by replacing \( A_L \) in Eq. 3 by some other characteristic reference area \( A_c \):

\[
f'' = 4C_D \frac{A_L}{A_o} \left( \frac{u_m}{u_x} \right)^x
\]  

The values of \( C_D \) and \( \chi \) will depend on the selected reference area.
Foliated trees are comprised of two plant parts, foliage and stem, that differ in e.g. flexibility. Therefore, the abundance of foliage in relation to the stem may be an important controlling factor for the reconfiguration and flow resistance of foliated vegetation. For instance, Wilson et al. (2008) compared ivy to the willows of Armanini et al. (2005) and found that the share of foliage to drag was larger for the species having more abundant foliage, i.e. a higher ratio of leaf area to the total frontal projected area. The abundance of foliage in relation to the stem can be parameterized by some form of foliage–stem reference area ratio, such as the leaf-area-to-stem-area ratio ($A_L/A_S$). The foliage–stem reference area ratio may be used e.g. in characterizing the vertical distribution of foliage at different relative submergences for the flow resistance prediction. For instance, trees with approximately uniform vertical distribution of foliage have been reported to have similar flow resistance per submerged $A_L$ at both partly and just submerged conditions (Järvelä, 2006; Kouwen & Fathi-Moghadam, 2000). These findings suggest that considering $A_L/A_S$ as a secondary area parameter (in addition to the primary area parameter, i.e. the characteristic reference area) may improve the predictive capabilities of flow resistance formulations. Of these two parameters, $A_L/A_S$ characterizes the relative importances of the foliage and stem while the characteristic reference area takes into account the size of the plant. Such a scaling parameter for size is needed since similar $A_L/A_S$ values may be obtained for plants of variable sizes (e.g. from twigs to a few meter tall saplings).

This paper investigates selected reference area properties of foliated deciduous vegetation for hydraulic considerations. Novel experimental data was obtained from Black Poplar ($Populus nigra$) stands formed in a laboratory flume. The drag forces were measured simultaneously for 3-8 poplar specimens while $A_P$ was recorded by underwater photography. The paper analyses the reconfiguration and frontal area reduction of the plants as well as explores the estimation of flow resistance with three characteristic reference areas (leaf area $A_L$, frontal projected area under flow $A_P$, and still-air frontal projected area $A_0$) and the foliage–stem reference area ratio (expressed as $A_L/A_S$). Measurements were conducted at the relative submergences of 0.3, 0.7 and 1.0 to examine whether the drag and reconfiguration differ between the partly and just submerged plants. The Black Poplars were compared to literature data on $Populus$ and $Salix$ species to analyze the capabilities of the selected reference areas and foliage–stem reference area ratio for characterizing the flow resistance and reconfiguration of foliated deciduous vegetation. The poplar specimens were 25 cm tall twigs collected from mature trees.
2. Methods

2.1 Hydraulic experiments with single poplars and poplar stands

Black Poplar (Populus nigra) was selected for this study since it is a species commonly growing on riparian areas. In the experiments, drag forces were measured at various flow velocities for single poplars in the foliated and defoliated condition as well as for several foliated poplar specimens positioned in plant stands of varying density and relative submergence. The tested poplar twigs were cut from two mature trees growing next to each other in a terrestrial habitat in Braunschweig, Germany. The catkins and seed tufts were removed prior to the experiments so that each specimen consisted of leaves and a woody stem. The stem height of the specimens was 23 cm while the height to the topmost leaves was approximately 25 cm (Figure 1a). As most of the specimens had a slightly bent stature, they were positioned in the flume so that they bent towards downstream in still water. The properties of the poplars in the investigated stands are documented in Table 1.

Experiments were carried out in a 32 m long, 0.6 m wide tilting laboratory flume in the hydraulic laboratory of the Leichtweiss-Institut für Wasserbau, Technische Universität Braunschweig, Germany. The bed roughness in the flume consisted of a rubber mat with 3 mm high pyramidal-shaped roughness elements. Discharge was controlled by a valve and measured by an inductive flow meter while water depth (h) was adjusted by a tailgate located 9 m downstream from the test section. The water depth and water surface slope were determined using five piezometers installed along the plant stand. Mean flow velocity (\(u_m\)) was calculated from the continuity equation neglecting the vegetation volume and is used in this paper as the reference velocity. All experiments were carried out with steady uniform flow conditions (in a spatially averaged sense), and the drag forces acting on up to eight vegetation elements were recorded using the drag force sensors (DFS) described in Schoneboom et al. (2008) and Schoneboom (2011). The sensors were installed below the flume bottom in the 1.5 m long test section, located 16 m downstream of the flume inlet, to ensure that they did not disturb the flow and that they could be easily rearranged to match the corresponding plant densities. Each DFS consists of a 140 mm long, 20 mm wide, and 3 mm thick bending steel beam that is connected to an aluminium base plate by a rigid joint (Figure 2). A freely movable aluminium head plate is fixed to the top of the steel beam in which a vegetation element is attached, acting as a cantilever when subjected to flow. The compression strains generated by the vegetation element are measured by two Wheatstone full bridge configurations formed by four strain gauges mounted at the positions 1 and 2, separated by the distance \(l\). The drag force \(F\) exerted onto the vegetation element is computed as

\[
F = \frac{M_1 - M_2}{l} \tag{5}
\]
where the bending moments $M_1$ and $M_2$ acting on positions 1 and 2 are determined from the compression strains and the properties of the steel beam according to Keil (1995). The measurement errors of the calibrated sensors were ±0.01 N for $F=0$-$0.5$ N, and ±0.02 N for $F=0.5$-$2$ N. The drag forces were recorded at the sampling rate of 200 Hz for three periods of 60 s which was found sufficient to reach a stable mean value. The data presented in this paper are based on the time-averaged drag forces that were obtained by computing the average value of the three 60 s periods.

Firstly, three single poplars were tested with only one specimen positioned in the flume at a time. The drag forces were measured for the same specimens in the foliated and defoliated condition (see Table 2), and the share of the foliage to drag was determined by subtracting the drag of the defoliated specimen from the drag of the foliated specimen. The defoliated specimens are referred to as stems in this paper. Secondly, poplar stands were investigated with the individual poplars arranged in a staggered pattern where the lateral spacing $a_y$ of the plants equaled to the longitudinal spacing $a_x$ of the plant rows (Figure 3). Half of the leaves were removed from selected specimens close to the flume walls to achieve a uniformly distributed plant density. The poplars formed a 5 m long stand extending approximately 1.5 m upstream and downstream of the test section (Figure 1b). The plant stand was preceded and followed by a 6 m long continuous vegetated area composed of artificial poplar elements (described by Schoneboom et al., 2008) to create a fully developed flow inside the stand. Five plant stands were examined: three just submerged stands ($h/H=1.0$) with the plant spacing of 0.20 m (hereafter $h/H=1.0 \_20S$), 0.30 m ($h/H=1.0 \_30S$) and 0.40 m ($h/H=1.0 \_40S$), respectively, as well as two partly submerged stands with the plant spacing of 0.30 m and $h/H=0.3$ ($h/H=0.3 \_30S$) and $h/H=0.7$ ($h/H=0.7 \_30S$) (Table 2). Thus, the plant density varied from 6.25 to 25.0 plants per $m^2$, with the sparsest spacing enabling only three plants to be attached to the force sensors. The water level was just above the top of the bent plants for the just submerged stands. For the partly submerged stands, the water level was slightly lowered towards the higher velocities to ensure that the amount of submerged foliage remained the same at all examined velocities despite the minor bending of the plants. Experiments with one just submerged stand took two days, and freshly cut specimens were collected for each of the three stands to ensure the vitality of the plants. The investigation of the two partly submerged stands lasted altogether three days and the same specimens were used in both stands.

The characteristic reference areas were determined according to the relative submergence, so that the areas below the plant height of 8 cm and 16 cm, respectively, were considered for the specimens with $h/H=0.3$ and 0.7. Three randomly selected specimens in each stand were photographed from the downstream direction with a submersible camera in still air before the hydraulic experiments and under flow at the different examined velocities. A 10 cm reference scale was positioned at the longitudinal mass centre of the foliage which was visually estimated for each measurement to take into account the increasing bending of the plants with velocity. The frontal projected areas in still air ($A_0$) and under flow...
(Ap) were obtained with image analysis software by manually delineating the contours of each specimen and using the single reference scale (Figure 1c). Later, A0 values were found to be negatively biased for three of the partly submerged plants that had a longitudinally bent stature, which resulted from the fact that the reference scale was positioned at the mass centre of the foliage of the entire 25 cm tall plant instead of at the mass centre of the foliage located below the plant heights of 8 cm and 16 cm. Therefore, variables comprising A0 were excluded from the statistical analyses. For the remaining specimens, the mean error in A0 and Ap was assumed to be ±10% due to the inaccuracies in the mass centre estimation and image analysis. Such errors resulting from image scaling are typical for flexible, bending vegetation (Sagnes, 2010). After the experiments, the leaves of each instrumented plant were collected and scanned, and the one-sided leaf areas (Al) were determined with image analysis software. Stem areas (As) were obtained by laying the stems flat on the scanner, and therefore As was slightly higher than the frontal projected stem area A0.5.

2.2. Data analyses

Statistical analyses were performed with Statistix 9.0 to examine the relationships between F and the characteristic reference areas A1, A0, and Ap as well as the leaf-area-to-stem-area ratio A1/As. Firstly, we analyzed whether F and Ap in relation to reference area differed between the three relative submergences. For this, F/As values were computed for each instrumented specimen while F/As and Ap/As values were derived for those three specimens per stand which had been photographed. As the measured velocities varied between the stands, the values at selected target velocities were interpolated from the power-type regression equations fitted between velocity and F/Al, F/As, and Ap/Al for each stand. The highest target velocity where values were obtained for the partly submerged plants was u=0.46 m/s. The differences in F/Al, F/As, and Ap/Al between the relative submergences were tested separately at four target velocities with Welch’s t-test for independent samples (Welch, 1947) which allows for unequal sample sizes and variances. The procedure involved firstly testing the differences between the two partly submerged conditions (h/H=0.3 and 0.7), after which the data of the two partly submerged stands were lumped together and compared to the just submerged condition (h/H=1.0). This approach based on two t-tests was chosen instead of an analysis of variance with the three relative submergences in order to improve the statistical power. Secondly, to examine whether the variation in flow resistance between the stands could be associated with plant properties, the differences in the plant properties were tested between the two partly submerged stands (group 1), and between the three just submerged stands (group 2) using analysis of variance with Welch’s F test (Table 1). Thirdly, we examined whether the prediction of F is improved when A0/As is used as a secondary area parameter in addition to the reference area A1. For this, linear regression equations with intercepts were fitted between F/Al and A1/As at each velocity separately for the partly and just submerged plants. In all statistical analyses, we considered probability p<0.05 significant and probability p<0.10 to suggest that there is some evidence against the null hypothesis. Fourthly, to characterize the drag and Ap with respect to velocity, power-type
regression equations were fitted between velocity and the measured \( \frac{A_p}{A_L} \), \( \frac{A_p}{A_0} \), \( \frac{F}{A_L} \), \( \frac{F}{A_P} \), and \( \frac{F}{A_0} \) including all examined specimens. Since \( A_0 \) values were not determined for the h/H=1.0_20S stand, they were estimated by multiplying \( A_L \) by the mean \( \frac{A_0}{A_L} \) of the other just submerged stands. In all analyses, \( u_m \) was used as the independent variable instead of the plant Reynolds number (\( Re=\frac{u_c l_c}{\nu} \)) since it is not clear which plant length scale should be used as the characteristic length \( l_c \) for flexible and foliated objects (e.g. Statzner et al., 2006), including foliated trees. For simply shaped elements, such as cylinders, the object Reynolds number can be clearly defined by using the cylinder diameter as \( l_c \). However, using the stem diameter as \( l_c \) for foliated vegetation does not adequately reflect the significant influence of the leaves. As a consequence, we decided not to report plant Reynolds numbers in this paper.

The capabilities of the different characteristic reference areas for estimating the vegetative friction factors \( f'' \) were analyzed by parameterizing Eq. 4. For this, \( f'' \) values were computed for each poplar stand from Eq. 2. To ensure the comparability of the parameter values of the Black Poplars to those documented in the literature, \( u_\chi=0.10 \text{ m/s} \) was selected and thus only experiments conducted at \( u_m \geq 0.10 \text{ m/s} \) were included. The parameter values were derived from power-type regression equations fitted to the data in the form of Eq. 4. Firstly, the parameter values were obtained with \( A_L \) as the reference area based on all the available data, and additionally only for the just submerged condition. Secondly, the capabilities of the three reference areas (\( A_L \), \( A_P \), and \( A_0 \)) for estimating \( f'' \) of the poplar stands were evaluated. Here, we used data of those three specimens per stand for which all three reference areas had been determined. The h/H=1.0_20S stand was excluded from this analysis since \( A_0 \) values were not measured for it. The root mean square error (RMSE), coefficient of determination (\( R^2 \)), and mean relative error were used as measures of fit.

The Black Poplars were compared to \textit{Populus} and \textit{Salix} species to improve the understanding of the reconfiguration and flow resistance of foliated deciduous vegetation. As there is only limited data available on \( A_0 \) and \( A_P \) for deciduous trees in water flows, we used data measured in air flows for 12-13 m tall Black Poplars (\textit{Populus nigra} var. \textit{italica}) by Koizumi et al. (2010), and for 1.9 m tall crowns of 3-5 m tall Black Cottonwoods (\textit{Populus trichocarpa}) and Trembling Aspens (\textit{Populus tremuloides}) by Vollsinger et al. (2005). These data were transformed to be comparable with the data measured in water flows by considering the density (\( \rho \)) and kinematic viscosity (\( \nu \)) of air and water at the investigated temperatures (Vogel, 1994). Denoting the values in air with the subscript a, the equivalent velocity in water (\( u=\frac{u_A \rho_A}{\rho} \)) was obtained from the Reynolds similarity while the equivalent drag force in water was derived from the \( C_D \) similarity as

\[
F = \frac{\rho}{\rho_A} \frac{u^2}{u_A^2} F_A \tag{6}
\]

The reliability of these similarity considerations for flexible vegetation is supported by Kouwen & Fathi-Moghadam (2000), who found that the flow resistance of four conifer species was similar in air and water flows. The Black Poplars...
we were also compared to Järvelä’s (2002, 2004) Goat Willows (Salix caprea) and Dittrich et al.’s (2012) artificial poplars, for which parameter values of Eq. 4 have been reported with $A_L$ as the reference area. The parameter values were also determined for the Sharp-stipuled Willows (Salix triandra x viminalis i.e. Salix x mollissima) of Järvelä (2006). The parameters were examined with a view on $A_L/A_S$, which was derived for each species from the reported $A_L$, $A_{0.5}$ or average stem diameter and height. The Vogel exponent $b$ was determined for all species from the power-type regression equations which were formed at the velocity range corresponding to that of the Black Poplar twigs.

3. Results

Figure 4 shows the simultaneously measured drag forces of the individual 3-8 specimens in the five poplar stands at the three investigated relative submergences. The range of $F$ was large for the individual specimens at the same relative submergence. However, the coefficient of variation (standard deviation divided by the mean) of $F$ decreased with increasing velocity, indicating that the greatest variability in drag occurred at lower velocities. The measured forces reflected the relative submergence of the plants, with the highest forces obtained for the just submerged plants. For all three relative submergences, the $F-u_m$ relationship appeared to be fairly linear at velocities over 0.1 m/s. However, the slopes of the lines connecting the measured forces varied among the specimens (Figure 4), revealing that each specimen had a unique reconfiguration pattern in relation to the mean velocity. The reconfiguration and frontal area reduction are analyzed in detail in Section 3.1 while Section 3.2 focuses on the different characteristic reference areas for the parameterization of the drag and flow resistance.

3.1 Reconfiguration and frontal area reduction of the Black Poplars

The foliated single Black Poplars had a Vogel exponent $b=-0.88$, so that their $F-u_m$ relationship was close to linear (Figure 5). This was consistent with the marked decrease in the frontal projected areas of the foliated poplars with velocity (see Figure 6a for the $A_P$ values of the specimens in the plant stands). By contrast, the defoliated stems had $b=0.23$, and thus the exponent of their $F-u_m$ relationship was slightly over 2. The approximately squared increase in drag agreed with the observation that increasing velocity resulted in only slight reduction in $A_P$ as well as induced some potentially drag-increasing vibration of the stems. Further, the stems of the foliated plants were observed to reduce their $A_P$ far less than the foliage despite the fact that the drag on the foliage induced some bending of the stems. The higher efficiency of the foliated plants to reduce their frontal projected area, and therefore the rate of increase in drag, was reflected in the decreasing share of the foliage to drag with velocity (Figure 5).

The measured $A_P$ of the foliated specimens in the plant stands differed depending on the relative submergence (Figure 6a). However, most of the variation in $A_P$ was explained by the leaf area $A_L$ (Figure 6b) and the still-air frontal
projected area $A_0$ (Figure 6c). $A_p$ of the just submerged specimens declined, compared to $A_0$, by 50% at $u_m = 0.2$ m/s and by 75% at $u_m = 0.6$ m/s. The changes in $A_p$ became smaller at the highest velocities, suggesting that the poplar twigs would have experienced only small further reduction in $A_p$ at velocities over 0.6 m/s. The poplars demonstrated a rather low frontal projected area in relation to the one-sided leaf area: $A_p/A_L$ was 0.2 at 0.1 m/s and 0.1 at 0.6 m/s.

Although a large scatter was found in $A_p/A_L$ and $A_p/A_0$ between the individual specimens, the power-type regression equations ($A_p/A_L$=0.087$u_m^{-0.37}$, $R^2$=0.77; $A_p/A_0$=0.28$u_m^{-0.40}$, $R^2$=0.76) could satisfactorily estimate the pattern of $A_p$ reduction with velocity.

Regarding to the effects of relative submergence, $A_p/A_L$ was similar for h/H=0.3 and h/H=0.7 at all four velocities (probability p=0.37-0.97). Although the partly submerged plants appeared to have slightly higher $A_p/A_L$ compared to the just submerged plants (Figure 6b), no significant differences were found between them at $u_m=0.10$ m/s and $u_m=0.32$ m/s (p=0.18-0.96). However, there was some evidence that $A_p/A_L$ was greater for the partly submerged plants at $u_m=0.21$ m/s and $u_m=0.46$ m/s (p=0.064-0.096). For all three relative submergences, the orientation of the leaves in the main flow direction was the main mechanism of frontal area reduction. However, the just submerged plants had a greater ability to bend their main stem and side-twigs downstream, and thus to cover their downstream leaves by the upstream leaves, which may explain their slightly lower $A_p/A_L$ compared to the partly submerged plants. On the other hand, reconfiguration (Vogel exponent) was similar for the partly (b=−1.01) and just submerged plants (b=−1.03). The negatively biased $A_0$ values for some of the partly submerged specimens (see Section 2.2) resulted in a larger variation and higher values of $A_p/A_0$ compared to the just submerged plants (Figure 6c).

### 3.2 Estimating the drag and flow resistance of the Black Poplars with three characteristic reference areas ($A_L$, $A_p$, and $A_0$) and the leaf-area-to-stem-area ratio ($A_l/A_s$)

The individual poplars demonstrated large scatter in the drag–reference area relationships, with some specimens having up to 100% higher drag per characteristic reference area than others. We focus first on the effects of relative submergence on the drag–reference area relationships. The partly submerged plants had higher drag per still-air frontal projected area ($F/A_0$) than the just submerged plants (Figure 7c), which was assumed to result from the biased $A_0$ values of three partly submerged specimens. Drag per one-sided leaf area ($F/A_L$) was similar for h/H=0.3 and h/H=0.7 at $u_m=0.10-0.32$ m/s (p=0.16-0.45) but slightly higher for h/H=0.3 at the highest examined velocity (p=0.035, Figure 7a).

$F/A_L$ was also similar between the partly and just submerged specimens at all velocities (p=0.14-0.88). Further, no differences were found in drag per frontal projected area under flow ($F/A_p$) between h/H=0.3 and h/H=0.7 (p=0.64-0.89), or between the partly and just submerged specimens (p=0.10-0.30, Figure 7b). Thus, both $A_L$ and $A_p$ could describe the drag at all investigated relative submergences for the poplar twigs having $A_L=300-2200$ cm² and $A_p=40-$
460 cm². However, the F/\(A_P\) values appeared to slightly increase with the relative submergence, which was explained by the fact that the share of the total hydraulically effective plant area that was not captured by \(A_P\) increased with increasing relative submergence. This was consistent with the slightly lower \(A_P/\lambda\) values for the just submerged specimens compared to the partly submerged specimens (see Section 3.1): the plants at higher relative submergences had a greater ability to bend and thus to decrease their \(A_P\) by covering downstream plant parts by the upstream parts.

Finally, regression equations including all relative submergences were fitted for \(F/A_L\) (\(F/A_L = 17.2u_m^{1.09}, R^2=0.89\)), \(F/\lambda\) (\(F/\lambda = 255u_m^{1.61}, R^2=0.93\)) and \(F/A_0\) (\(F/A_0 = 48.6u_m^{0.93}, R^2= 0.86\)).

We also investigated the effects of the foliage–stem reference area ratio on drag. For the single plants, foliage contributed 98% of the drag at 0.10 m/s and 74% at 0.87 m/s, revealing that the drag generated by the stem became more important at higher velocities (Figure 5). Although the mean share of foliage to drag was high (86%), it was lower than that suggested by the foliage–stem reference area ratios \(A_L/A_S\) (98%) and \(A_{\lambda}/A_{\lambda S}\) (95%, Table 1). With the reference area definitions \(A_L\) and \(A_S\), the stem generated on average 10 times higher drag per unit reference area compared to the foliage. For instance, \(F/A_S\) was approximately 52 N/m² for the defoliated stems at 0.47 m/s while \(F/A_L\) was 6.8 N/m² for the foliated specimens. These findings suggested that the large scatter observed in the \(F/A_L\) values of the individual poplars could be partly due to the variation in their \(A_L/A_S\). Thus, we analyzed whether the estimation of \(F\) could be improved by using \(A_L/A_S\) as a secondary area parameter in addition to the primary explanatory parameter \(A_L\).

For the just submerged plants, the regression equations between \(F/A_L\) and \(A_L/A_S\) had negative slopes at all velocities (Figure 8a). For instance, \(F/A_L\) decreased from 12 N/m² at \(A_L/A_S=50\) to 9 N/m² at \(A_L/A_S=75\) for the highest examined velocity. It is acknowledged that correlations between ratios sharing a common element (such as \(A_L\) for \(F/A_L\) and \(A_L/A_S\)) may be spurious. However, the \(R^2\) values between \(F/A_L\) and \(A_L/A_S\) (\(R^2=0.29-0.70\)) were higher than the theoretical null correlation for two uncorrelated ratios for which the denominator of one ratio equals the numerator of the other (\(R^2=0.25\); Benson, 1965). Furthermore, for the examined just submerged plants, \(A_L\) and \(A_L/A_S\) could be considered as two almost independent parameters since the coefficient of determination between them was low (\(R=0.16\)). Thus, the obtained relationships between \(F/A_L\) and \(A_L/A_S\) were not entirely spurious, and it was concluded that \(A_L/A_S\) as the secondary explanatory parameter improved the prediction of \(F\) for the just submerged plants. The partly submerged plants also demonstrated negative slopes between \(F/A_L\) and \(A_L/A_S\), but most of the regressions were not significant (Figure 8b). This indicated that \(A_L/A_S\) provided only little improvement for the estimation of \(F\) for the partly submerged plants, which was explained by the fact that \(A_L/A_S\) did not provide much additional information about the plants as the correlation between \(A_L\) and \(A_L/A_S\) was notable (\(R^2=0.59\)). On the whole, the decreasing \(F/A_L\) with increasing \(A_L/A_S\) was presumed to result from the fact that the stem contributed a lower share to the total drag as its share of the total reference area decreased. In addition, the effect of \(A_L/A_S\) was stronger at higher velocities, which was...
associated with the larger share of the stem to drag due to the more efficient reconfiguration of the foliage as velocity increased.

The experimentally obtained vegetative friction factor $f''$ decreased as a power function of velocity for all investigated stands, reflecting the reconfiguration of the plants. For instance, for the densest stand with the spacing $a=0.2$ m and $A_L/A_b =3.25$, $f'$ declined from 6.17 at 0.09 m/s to 0.83 at 0.56 m/s, corresponding to Manning’s $n$ of 0.202 and 0.072, respectively. Further values of $f''$ may be obtained simply by multiplying the $f''/(A_L/A_b)$ values shown in Figure 9a by the corresponding $A_L/A_b$ values shown in Table 2. The parameters of the vegetative friction factor formulation (Eq. 4) were fitted using data of all the examined relative submergences because the drag–reference area relationships were mostly similar for $h/H=0.3-1.0$. The parameters derived for the Black Poplars using all available data and $A_L$ as the characteristic reference area are shown in the first row of Table 3. At the velocity range of 0.10-0.61 m/s, $C_{Dx}$ was 0.33 and $\chi$ was -1.03. The parameter values remained the same when only the just submerged stands were included (at the $A_L/A_b$ range of 0.95-3.25). Comparing the stands revealed that $f''$ per $A_L/A_b$ was constantly higher for the $h/H=1.0_{-20S}$ stand than for the $h/H=1.0_{-40S}$ stand. This finding may be explained by $A_L/A_b$, the effect of which on $F/A_L$ was shown above for the individual specimens, as the $h/H=1.0_{-20S}$ stand had a significantly lower mean $A_L/A_S$ than the $h/H=1.0_{-40S}$ stand (Table 1). Similarly, the $f''/(A_L/A_b)$ values of the $h/H=0.3_{-30S}$ stand were higher than those of the $h/H=0.7_{-30S}$ stand in association with the significantly lower $A_L/A_S$ of the $h/H=0.3_{-30S}$ stand. Next, Eq. 4 was applied to analyze the capabilities of $A_L$, $A_P$, and $A_b$ for estimating $f''$ of the stands (Figure 9). The results are directly comparable as the same specimens (those three per stand for which all reference areas were determined) were used for the three characteristic reference areas. All formulations had a high $R^2$ (Table 3), indicating that Eq. 4 could estimate the pattern of reconfiguration with all three reference areas. $A_L$ had an equal mean error as $A_P$ but a lower RMSE. The markedly higher mean error and RMSE for $A_b$ were associated with the biased $A_b$ values for three of the partly submerged specimens, which led to high $f''/(A_L/A_b)$ values particularly for the stand with $h/H=0.7$. The choice of the characteristic reference area affected the derived parameter values: the drag coefficient $C_{Dx}$ was the lowest for $A_L$ since this reference area acquired the highest values while the vegetation parameter $\chi$ was the largest for $A_P$ which takes into account the frontal area reduction with velocity.

4. Discussion

The extensive dataset allowed analyzing the capabilities of the three characteristic reference areas (one-sided leaf area $A_L$, frontal projected area under flow $A_P$, and still-air frontal projected area $A_b$) for estimating the flow resistance of foliated Black Poplar twigs at $h/H=0.3-1.0$. As the relative submergence did not have substantial effects on the drag and $A_P$, the fitted parameters of Eq. 4 and the derived regression equations may be applied to predict the flow resistance and...
A_p for both partly and just submerged foliated Black Poplar twigs or saplings. Comparing the results with selected literature data enabled making some observations regarding to the reconfiguration and frontal area reduction (Section 4.1) as well as the flow resistance estimation (Section 4.2) for foliated deciduous species.

4.1 Reconfiguration and frontal area reduction of foliated deciduous species

The foliated Black Poplars were more efficient in reducing their A_p and in reconfiguration compared to the defoliated stems, suggesting that the efficiency of frontal area reduction and reconfiguration improves with increasing foliage–stem reference area ratio. Comparing the Vogel exponent (b=−1.03) to the exponent of the A_p/A_o=\text{u}_m regression equation (-0.37) indicated that frontal area reduction caused only approximately half of the reconfiguration for the foliated plants. This confirmed the existence of other mechanisms that notably contributed to the reconfiguration, such as the increasingly streamlined shape of the twigs with velocity. Comparison to other Populus species revealed that the A_p/A_o values of the just submerged Black Poplar twigs were 35–42% and 44% lower than those measured by Vollsinger et al. (2005) for the 1.9 m tall Black Cottonwoods (Populus trichocarpa) and Trembling Aspens (Populus tremuloides), respectively. The lower A_p/A_o values for the Black Poplars likely partly resulted from their higher foliage–stem reference area ratio (A_o/f/A_o,s=-25) compared to that for the Black Cottonwoods (A_o/f/A_o,s=3.6). However, the effects of the foliage–stem reference area ratio need to be elucidated in more detail by performing further experiments with several species in the same flow medium. Despite the differences in the A_p/A_o values, the pattern of A_p/A_o reduction was fairly similar for all three species at the investigated velocity range. Moreover, the Vogel exponents computed from Vollsinger et al. (2005) indicated that the reconfiguration of the Black Poplar twigs (b=−1.03) was almost equal to that of the Black Cottonwoods (b=−0.94); however, reconfiguration was less efficient for the Trembling Aspens (b=−0.65).

The present Black Poplar twigs were also slightly more efficient in reconfiguration than Koizumi et al.’s (2010) 12-13 m tall mature Black Poplars (b=−0.83). As a whole, the capacity for reconfiguration can be regarded as fairly similar for the examined Populus specimens considering that they represented varying stages of development and originated from different geographical locations.

In comparison to similar-sized deciduous species, reconfiguration of the Black Poplars was almost equal to that of Järvelä’s (2006) 25 cm tall Sharp-stipuled Willows (Salix triandra x viminalis, i.e., Salix x mollissima, b=−0.90) but more efficient than that of Järvelä’s (2002, 2004) 0.7 m tall Goat Willows (Salix caprea, b=−0.57). For instance, the friction factor at 0.60 m/s for the Black Poplars was 16% of that at 0.10 m/s while it was 20% for the Sharp-stipuled Willows and 36% for the Goat Willows (Figure 10c). Comparing the three natural species, reconfiguration appeared to improve with the increasing A_f/A_o (Table 4; \( \chi \) equals the Vogel exponent b). On the other hand, the more efficient reconfiguration of the Black Poplars compared to the artificial poplars (b=−0.74, Dittrich et al., 2012) was expected to
result from the differences in their mechanical properties. For instance, the tested artificial poplars had a fairly rigid blossom which constrains the frontal area reduction of their top leaves (Aberle et al., 2011).

4.2 Estimating the flow resistance of foliated deciduous species with the different reference areas

Each of the three characteristic reference areas, determined from three representative plants, satisfactorily estimated the friction factors of the Black Poplar stands, but $A_L$ and $A_P$ provided the most accurate predictions due to the measurement biases in $A_0$. Only few studies have compared the different reference areas as predictors of flow resistance for foliated deciduous vegetation, with most of the studies reporting data on only one reference area, typically $A_0$, or focusing on other plant properties (e.g. Kane et al., 2008; Xavier, 2009). Nevertheless, Vollsinger et al. (2005) found $A_P$ to be a better predictor of drag than $A_0$ for each of the five foliated deciduous species examined in a wind tunnel. A similar finding has been obtained for three conifer species tested in a wind tunnel (Rudnicki et al., 2004). For the Black Poplars, large variation was found in the drag–reference area relationships between the individual specimens, which may be partly attributed to the spatially heterogeneous flow field that is typical for plant stands (e.g. Aberle et al., 2011; Siniscalchi et al., 2012). Using the same measurement system and comparable flow conditions, Schoneboom et al. (2010) found that the spatial variability of drag ranged to over 50% for identical artificial poplars in a stand due to the complex flow field and wake flows. In the present experiments, the flow field heterogeneity was expected to be high because each natural poplar had a unique structure, shape and pattern of bending.

Comparing the drag–reference area relationships of several foliated species revealed that the $F/A_0$ values for the present Black Poplars were on average 74% of those for tall Black Poplars computed from Koizumi et al. (2010), and 43-56% of those for Trembling Aspens and 53-57% of those for Black Cottonwoods computed from Vollinger et al. (2005) (Figure 10a). Since Koizumi et al. (2010) obtained the $A_0$ values by approximating the shapes of the crowns as ellipsoids, the $F/A_0$ values for the tall Black Poplars would have been still higher if the effective $A_0$ had been used. The lower $F/A_0$ values were in accordance with the greater efficiency for frontal area reduction of the Black Poplar twigs compared to the Black Cottonwoods and Trembling Aspens (see Section 4.1). On the other hand, $F/A_P$ of the Black Poplar twigs equaled the values derived from Vollinger et al. (2005) for the two other Populus species (Figure 10b). The similar $F/A_P$, as opposed to the dissimilar $F/A_0$, between the species reflects the fact that $A_P$ takes into account the differing capacity of the species to achieve a hydraulically efficient shape under flow. Therefore, $A_P$ as the reference area may enable estimating the drag for several related species of similar size by the same $F/A_P$ relationship. However, obtaining accurate frontal projected areas for flexible plants is difficult as the scaling of the photos is easily biased (Sagnes, 2010). Furthermore, the difficulties in estimating or determining $A_P/A_0$ or $A_0/A_b$ for floodplain reaches complicate the use of these reference areas in practical hydraulic engineering whereas the third examined reference
area, $A_l/A_b$, can be obtained for instance with terrestrial laser scanning (Antonarakis et al., 2010). According to the various field data compiled by Jalonen et al. (2013), natural shrub and tree stands have a mean $A_l/A_b$ of 1.0-5.1, so that the $A_l/A_b$ range of the examined poplar stands was reasonably representative of the conditions found in the nature. In addition, the Manning’s $n$ values derived for the densest poplar stand fell close to the value range typically associated with floodplains growing woody vegetation (e.g. Chow, 1959). However, relationships between drag or resistance coefficients and $A_l$ for woody vegetation have been reported in only few studies, such as Kouwen & Fathi-Moghadam (2000). In addition, $f''/(A_l/A_b)$ values have been derived for stands of two Salix species by Järvelä (2004, 2006). As $f''$ is related to $F$ through Eq. 2, the variation in $f''/(A_l/A_b)$ among the species reflects the between-species differences in $F/A_L$. The $f''/(A_l/A_b)$ values of the present Black Poplars were on average only 46% of those for Järvelä’s (2004) Goat Willows and 54% of those for Järvelä’s (2006) Sharp-stipuled Willows (Figure 10c). These differences are likely partly explained by the variation in the foliage–stem reference area ratio between the species, which is discussed in the next paragraphs.

The foliage–stem reference area ratio appeared to be an important parameter for characterizing the flow resistance of foliated vegetation since it is a direct measure of the relative shares of the two plant parts, foliage and stem, that were shown to differ in drag and reconfiguration. For instance, the increasing leaf-area-to-stem-area ratio ($A_l/A_S$) was found to decrease the $F/A_L$ values of the foliated Black Poplars, presumably due to the decreasing share of the stem to drag. Therefore, predicting flow resistance with $A_l$ can generally be expected to have the highest accuracy when the share of foliage to drag is high, or when $A_l/A_S$ is similar to that of the plants used for deriving the parameter values. For the present Black Poplars, the average share of foliage to drag (86%) was high enough that the friction factors of the poplar stands could be estimated accurately by $A_l$. In addition, the large mean $A_l/A_S$ at all relative submergences (Table 1) was expected to explain the fact that the drag and $A_p$ in relation to the reference areas did not differ between the partly and just submerged poplars. However, we suppose that the foliage–stem reference area ratio is important when plants at different foliation conditions are considered. For instance, the $F/A_L$ values obtained in this study for the Black Poplar twigs were on average only half of those derived by Schoneboom (2011, Figures 4.1 and 4.2) for similar-sized Black Poplar twigs collected from a nearby tree but having a 3/4 lower $A_L$. It therefore appears that predicting drag with $A_l$ can be improved by taking into account $A_l/A_S$.

In addition to the within-species differences discussed above, the foliage–stem reference area ratio seemed to be related to the between-species differences in flow resistance. Firstly, comparing the Black Poplars to ivy (Glechoma hederacea, Wilson et al., 2008) and White Willows (Salix alba, Armanini et al., 2005) revealed that the share of foliage to drag decreased with $A_l/A_S$: foliage contributed 86% of the drag for the Black Poplars ($A_l/A_S=57$), approximately 60% for...
ivy ($A_L/A_S=9$) and up to 40% for the White Willows ($A_L/A_S=4$). In general, the share of foliage to drag may range from 25 to 75% for 1.8-4.5 m tall alders, willows and poplars (Xavier, 2009; Dittrich et al., 2012). Secondly, Figure 10c and Table 4 show that of the three natural species for which $f''/(\Sigma A_L/A_0)$ values were computed, the Black Poplars having the highest $A_L/A_S$ demonstrated the lowest $f''/(A_L/A_0)$ while the Goat Willows having the lowest $A_L/A_S$ demonstrated the highest $f''/(A_L/A_0)$. Thus, the differences in $f''/(A_L/A_0)$ between the species were assumed to be partly caused by the fact that the stem is not taken into account in Eq. 4 when $A_L$ is used as the reference area. On the whole, it seems that the foliage–stem reference area ratio, parameterized e.g. as $A_L/A_S$, is a useful property for characterizing plants of different sizes, ages, and foliation conditions. More detailed experiments are under way to determine to which extent between-species variation in drag results from differences in $A_L/A_S$ as opposed to differences in the material properties of the leaves and stems among species.

5. Conclusions

This paper investigated four reference area properties for foliated Black Poplars (Populus nigra), providing new insight into the drag, reconfiguration and flow resistance of natural foliated vegetation. Each of the examined characteristic reference areas ($A_L$, $A_P$, and $A_0$) could satisfactorily estimate the flow resistance of the poplar stands. However, $A_L$ appeared the most suitable for practical applications as it can be readily obtained for natural plant stands in field conditions. The foliage–stem reference area ratio (parameterized as $A_L/A_S$) was an important controlling factor for the drag and frontal area reduction of the poplars. Firstly, a higher $A_L/A_S$ was inferred to improve the reconfiguration due to the more efficient frontal area reduction of the leaves compared to the stems. Secondly, the increasing $A_L/A_S$ reduced the drag per $A_L$ due to the decreasing contribution of the stem to drag. In consequence, flow resistance estimation with $A_L$ may be improved by using $A_L/A_S$ as a secondary area parameter. As the poplar stands had a high $A_L/A_S$ at all relative submergences, the same parameter values could be used for estimating the vegetative friction factor (Eq. 4) and $A_P$ at low to just submerged conditions. Comparison to two Salix species suggested that the foliage–stem reference area ratio was an important factor explaining the between-species variation in flow resistance per $A_L$. Finally, the drag per $A_P$ was found to be similar for three different Populus species ranging from 0.25 to 1.9 m in height.

Acknowledgements

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**List of most important symbols and abbreviations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>plant spacing</td>
</tr>
<tr>
<td>( A_h )</td>
<td>ground area</td>
</tr>
<tr>
<td>( A_c )</td>
<td>characteristic reference area</td>
</tr>
<tr>
<td>( A_L )</td>
<td>one-sided leaf area</td>
</tr>
<tr>
<td>( A_L/A_S )</td>
<td>leaf-area-to-stem-area ratio</td>
</tr>
<tr>
<td>( A_F )</td>
<td>frontal projected area under flow</td>
</tr>
<tr>
<td>( A_S )</td>
<td>one-sided area of the stem laid flat on the scanner</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>still-air frontal projected area</td>
</tr>
<tr>
<td>( A_{0,S} )</td>
<td>still-air frontal projected area of the stem</td>
</tr>
<tr>
<td>( A_{0,F} )</td>
<td>still-air frontal projected area of the foliated plant</td>
</tr>
<tr>
<td>b</td>
<td>Vogel exponent</td>
</tr>
<tr>
<td>( C_D )</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>( C_{D,s} )</td>
<td>species-specific drag coefficient</td>
</tr>
<tr>
<td>DFS</td>
<td>drag force sensor</td>
</tr>
<tr>
<td>F</td>
<td>drag force</td>
</tr>
<tr>
<td>( f' )</td>
<td>fiction factor due to bed friction</td>
</tr>
<tr>
<td>( f'' )</td>
<td>vegetative friction factor</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>h</td>
<td>water depth</td>
</tr>
<tr>
<td>H</td>
<td>plant height</td>
</tr>
<tr>
<td>( h/H )</td>
<td>relative submergence</td>
</tr>
<tr>
<td>LAI</td>
<td>leaf area index ((A_L/A_b))</td>
</tr>
<tr>
<td>R</td>
<td>hydraulic radius</td>
</tr>
<tr>
<td>( u_c )</td>
<td>characteristic approach velocity</td>
</tr>
</tbody>
</table>
\[ u_m \] mean velocity

\[ u_\chi \] lowest velocity used in determining \( \chi \)

\( \chi \) vegetation parameter

**References**


Sagnes, P., 2010. Using multiple scales to estimate the projected frontal surface area of complex three-dimensional shapes such as flexible freshwater macrophytes at different flow conditions. Limnol. Oceanogr.: Methods 8, 474–483.


Welch, B.L., 1947. The generalization of 'Student's' problem when several different population variances are involved. Biometrika 34, 28-35.


**Figure captions**

Figure 1 A typical Black Poplar specimen (a), and a poplar stand in the test section of the flume with the drag force sensors below the flume bottom (b). The frontal projected areas under flow were delineated from underwater photographs taken against the main flow direction using the 10 cm reference scale (c).

Figure 2 A schematic drawing showing a natural plant attached to the drag force sensor.

Figure 3 The 1.5 m long test section showing the staggered pattern of the plants and the three plant densities with the spacing of 0.40 m (40S), 0.30 m (30S) and 0.20 m (20S). The plants attached to the drag force sensors are highlighted in orange.

Figure 4 Measured drag force as a function of mean velocity for the individual Black Poplar specimens in the five stands (see Table 2 for stand descriptions).

Figure 5 Drag forces of the three single poplars in the foliated and defoliated conditions, and the mean share of foliage to the drag.

Figure 6 Frontal projected area under flow $A_P$ (a), $A_P$ per leaf area (b), and $A_P$ per still-air frontal projected area (c) for the three relative submergences. Error bars are ±1 standard error. No significant differences were found in $A_P/A_L$ between the relative submergences; differences in $A_P/A_0$ were not tested.

Figure 7 Drag force per leaf area (a), per frontal projected area under flow (b), and per still-air frontal projected area (c). Error bars are ±1 standard error. Significant differences ($p<0.05$) in $F/A_L$ between the partly submerged specimens ($h/H=0.3$ and $h/H=0.7$) are marked with a and b; no further significant differences were found.

Figure 8 Linear regressions between drag per leaf area ($F/A_L$) and leaf-area-to-stem-area-ratio ($A_L/A_S$) at the different velocities for the just submerged (a) and partly submerged plants (b). $R^2$ values are shown for the significant regressions ($p<0.05$).

Figure 9 Experimentally obtained friction factors $f''$ of four plant stands normalized with $A_L/A_b$ (a), $A_P/A_b$ (b) and $A_0/A_b$ (c). The figures also show the power fit from which the parameter values of Eq. 4 were derived (the parameter values and goodness-of-fit statistics are shown in Table 3).
Figure 10 Drag per still-air frontal projected area (a), drag per frontal projected area under flow (b), and vegetative friction factor normalized with $A_l/A_b$ (c) for the Black Poplar twigs and other deciduous species. The $f''/(A_l/A_b)$ curves were drawn using the derived parameter values of Eq. 3 shown in Table 4.

**Table captions**

Table 1 Average properties of the Black Poplars in each stand (standard deviation in parentheses). The differences in the properties were tested firstly between the two partly submerged stands (for which $h/H < 1.0$, group 1), and secondly between the three just submerged stands ($h/H = 1.0$, group 2) (see Section 2.2 for details).

Table 2 Experimental conditions for the single poplars and poplar stands.

Table 3 Calibrated parameters, boundary conditions, and goodness-of-fit statistics for estimating $f''$ of the Black Poplar stands with Eq. 4. The first row shows the values obtained using all data and $A_L$ as the reference area. The three lowest rows report the results of the comparison of the reference areas $A_L$, $A_p$, and $A_0$.

Table 4 Parameter values and boundary conditions of Eq. 3 derived for the Black Poplars and other foliated deciduous species in plant stands using $A_L/A_b$ as the reference area ($A_L/A_b$ is usually referred to as leaf area index LAI).
Figure 4

Partly submerged

Just submerged

\[ F(N) \]

\[ h/H=0.3_{30S} \]

\[ h/H=0.7_{30S} \]

\[ h/H=1.0_{20S} \]

\[ h/H=1.0_{30S} \]

\[ h/H=1.0_{40S} \]
Figure 5

- $F (N)$
- $u_m (m/s)$
- Share of foliage to $F$

Legend:
- $\Diamond$ Poplar1 (Foliated)
- $\Delta$ Poplar2 (Foliated)
- $\Box$ Poplar3 (Foliated)
- $\Diamond$ Poplar1 (Defoliated)
- $\Delta$ Poplar2 (Defoliated)
- $\Box$ Poplar3 (Defoliated)
- + Share of foliage to $F$
Figure 6

(a)  

(b)  

(c)
Figure 7

(a) $F/A_0$ (N/m$^2$) vs. $u_m$ (m/s) for different $h/H$ ratios.

(b) $F/A_P$ (N/m$^2$) vs. $u_m$ (m/s) for different $h/H$ ratios.

(c) $F/A_0$ (N/m$^2$) vs. $u_m$ (m/s) for different $h/H$ ratios.
Figure 8

(a) $R^2 = 0.43$

(b) $R^2 = 0.70$

Figure 8
Figure 9

Predicted values for different h/H ratios at 30S and 40S:

- a) $f''/(A_p/A_b)$ vs. $u_m$ (m/s)
- b) $f''/(A_p/A_b)$ vs. $u_m$ (m/s)
- c) $f''/(A_p/A_b)$ vs. $u_m$ (m/s)
Black Poplar (present study)

Goat Willow (Järvelä 2004)

Sharp-stipuled Willow (Järvelä 2006)

Artificial poplar (Dittrich et al. 2012)

Black Poplar (present study)

Black Cottonwood (Vollsinger et al. 2005)

Trembling Aspen (Vollsinger et al. 2005)

Black Poplar (Koizumi et al. 2010)
Table 1

<table>
<thead>
<tr>
<th>Stand</th>
<th>Group for statistical tests</th>
<th>No of specimens *</th>
<th>Leaf area A_L (cm²)</th>
<th>Stem area A_S (cm²)</th>
<th>Still-air frontal projected area A_0 (cm²)</th>
<th>A_L/A_S (-)</th>
<th>A_0/A_L (-)</th>
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<tr>
<td>Single</td>
<td>-</td>
<td>3</td>
<td>1190 (120)</td>
<td>21 (3.1)</td>
<td>18 (0.29) / 370 (38) **</td>
<td>57 (13)</td>
<td>0.31 (0.05)</td>
</tr>
<tr>
<td>h/H=0.3_30S</td>
<td>group 1</td>
<td>7</td>
<td>400 (130)</td>
<td>10 (1.1)</td>
<td>130 (59)</td>
<td>41 (14) a</td>
<td>0.32 (0.04)</td>
</tr>
<tr>
<td>h/H=0.7_30S</td>
<td>group 1</td>
<td>7</td>
<td>1030 (130)</td>
<td>18 (2.6)</td>
<td>280 (57)</td>
<td>58 (8.9) b</td>
<td>0.27 (0.07)</td>
</tr>
<tr>
<td>h/H=1.0_20S</td>
<td>group 2</td>
<td>8</td>
<td>1300 (230) A</td>
<td>22 (3.6)</td>
<td>-</td>
<td>58 (6.2) A</td>
<td>-</td>
</tr>
<tr>
<td>h/H=1.0_30S</td>
<td>group 2</td>
<td>6</td>
<td>1730 (290) B</td>
<td>27 (5.3)</td>
<td>440 (6.9)</td>
<td>65 (5.3) AB</td>
<td>0.28 (0.04)</td>
</tr>
<tr>
<td>h/H=1.0_40S</td>
<td>group 2</td>
<td>3</td>
<td>1520 (81) AB</td>
<td>21 (1.5)</td>
<td>530 (57)</td>
<td>72 (2.6) B</td>
<td>0.35 (0.02)</td>
</tr>
<tr>
<td>Partly submerged (h/H&lt;1.0)</td>
<td>-</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>49 (14)</td>
<td>0.30 (0.06)</td>
</tr>
<tr>
<td>Just submerged (h/H=1.0)</td>
<td>-</td>
<td>17</td>
<td>1490 (300)</td>
<td>24 (4.5)</td>
<td>490 (59)</td>
<td>63 (7.4)</td>
<td>0.31 (0.05)</td>
</tr>
</tbody>
</table>

Note: The properties that significantly differ (p<0.05) between the two stands in group 1 are denoted by the letters a and b, while those differing between the three stands in group 2 are denoted by A and B. Only differences in ratios (A_L/A_S and A_0/A_L) were tested between the partly submerged stands (group 1), while differences in all properties were tested between the just submerged stands (group 2).

* No of specimens was three per stand for the variables incorporating A_0 or A_P.

** For the single plants, the first figure is A_0 of the stem (i.e. A_0,S), while the second figure is A_0 of the foliated plant (A_0,F).
Table 2

<table>
<thead>
<tr>
<th>Stand</th>
<th>$h/H$ (-)</th>
<th>Spacing a (m)</th>
<th>Plant density ($A_d/A_h$)</th>
<th>No of instrumented plants</th>
<th>Slope (%)</th>
<th>$h$ (cm)</th>
<th>$u_m$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>1 at a time, 3 in total</td>
<td>0.003–0.20</td>
<td>18.2–29.9</td>
<td>0.10–0.87</td>
</tr>
<tr>
<td>$h/H=0.3_30S$</td>
<td>0.3</td>
<td>0.30</td>
<td>11.1</td>
<td>0.44</td>
<td>7</td>
<td>0.07–0.53</td>
<td>7.5–8.7</td>
</tr>
<tr>
<td>$h/H=0.7_30S$</td>
<td>0.7</td>
<td>0.30</td>
<td>11.1</td>
<td>1.15</td>
<td>7</td>
<td>0.07–0.56</td>
<td>15.2–16.7</td>
</tr>
<tr>
<td>$h/H=1.0_20S$</td>
<td>1.0</td>
<td>0.20</td>
<td>25.0</td>
<td>3.25</td>
<td>8</td>
<td>0.24–1.90</td>
<td>19.9–25.9</td>
</tr>
<tr>
<td>$h/H=1.0_30S$</td>
<td>1.0</td>
<td>0.30</td>
<td>11.1</td>
<td>1.92</td>
<td>6</td>
<td>0.04–0.24</td>
<td>23.9–25.2</td>
</tr>
<tr>
<td>$h/H=1.0_40S$</td>
<td>1.0</td>
<td>0.40</td>
<td>6.25</td>
<td>0.95</td>
<td>3</td>
<td>0.07–0.71</td>
<td>18.4–25.0</td>
</tr>
<tr>
<td>Definition of characteristic reference area ($A_c$)</td>
<td>No of sampled plants per stand</td>
<td>Range of reference area per ground area ($A_c/A_b$)</td>
<td>$h/H$</td>
<td>$C_{ov}$</td>
<td>$u_x$</td>
<td>$\chi$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$A_c$, all data</td>
<td>3-8</td>
<td>0.44-3.25</td>
<td>0.3-1.0</td>
<td>0.33</td>
<td>0.10</td>
<td>-1.03</td>
<td>0.96</td>
</tr>
<tr>
<td>$A_L$</td>
<td>3</td>
<td>0.44-1.80</td>
<td>0.3-1.0</td>
<td>0.30</td>
<td>0.10</td>
<td>-1.02</td>
<td>0.98</td>
</tr>
<tr>
<td>$A_P$</td>
<td>3</td>
<td>0.05-0.34</td>
<td>0.3-1.0</td>
<td>1.43</td>
<td>0.10</td>
<td>-0.59</td>
<td>0.93</td>
</tr>
<tr>
<td>$A_0$</td>
<td>3</td>
<td>0.15-0.49</td>
<td>0.3-1.0</td>
<td>1.05</td>
<td>0.10</td>
<td>-1.11</td>
<td>0.93</td>
</tr>
<tr>
<td>Species</td>
<td>$C_d$</td>
<td>$u_r$</td>
<td>$\chi$</td>
<td>$A_d/A_r$ range</td>
<td>$h/H$ (-)</td>
<td>$A_d/A_t$</td>
<td>Reference</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-------</td>
<td>-------</td>
<td>--------</td>
<td>-----------------</td>
<td>-----------</td>
<td>-----------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Black Poplar (Populus nigra)</td>
<td>0.33</td>
<td>0.10</td>
<td>-1.03</td>
<td>0.4-3.2</td>
<td>0.3-1.0</td>
<td>57</td>
<td>Present study</td>
</tr>
<tr>
<td>Goat Willow (Salix caprea)</td>
<td>0.43</td>
<td>0.10</td>
<td>-0.57</td>
<td>1.3-3.2</td>
<td>0.4-1.0</td>
<td>-20</td>
<td>Järvelä (2002, 2004)</td>
</tr>
<tr>
<td>Sharp-stipuled Willow (Salix triandra x viminalis)</td>
<td>0.53</td>
<td>0.10</td>
<td>-0.90</td>
<td>0.7-1.9</td>
<td>1.0</td>
<td>-30</td>
<td>Järvelä (2006)</td>
</tr>
<tr>
<td>Artificial poplar in a staggered pattern</td>
<td>0.50</td>
<td>0.11</td>
<td>-0.74</td>
<td>0.4-1.7</td>
<td>1.0</td>
<td>-50</td>
<td>Dittrich et al. (2012)</td>
</tr>
</tbody>
</table>
Highlights:

New insights into the flow resistance of foliated vegetation were obtained
We measured drag and alternative reference areas for natural poplars in a flume
Partly and just submerged plants had similar drag and frontal area per reference area
Drag and reconfiguration were controlled by the foliage–stem reference area ratio
The alternative reference areas satisfactorily predicted the drag and flow resistance