

Modeling flow in 3D vegetation structures for wildland fire simulations using a localized drag force formulation

Eric Mueller¹, Kunhyuk Sung¹, Anthony Hamins¹

¹Fire Research Division, NIST, 100 Bureau Drive, Gaithersburg, MD 20899, USA

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Abstract

The interaction of wind and vegetation through drag forces plays an important role in wildland fire behavior and is, therefore, a key component to detailed models of such fires. This study evaluates a typical approach applied in Computational Fluid Dynamics (CFD) wildland fire models. Vegetation is represented as a dispersed media comprised of numerous subgrid-scale particles, each contributing to the total local drag. The numerical approach was evaluated against force and velocity measurements made in a small-scale wind tunnel. Specimens of differing structural form were tested, starting from a collection of screens which are well-represented by the model formulation and increasing in complexity to bundles of thin wood fibers (excelsior), and on to branches of real trees. This increasing complexity enabled a progressive evaluation of the limits of the model assumptions. Though careful characterization of sample properties, e.g. the packing ratio and surface-to-volume ratio, was required, the model performed well using *a priori* assumptions for specimens which had simple uniform or statistically isotropic particle arrangements. For real vegetation, however, empirical tuning of the model parameters was required. It has been suggested that this is linked to both increased complexity in particle orientation and the potential flexibility in plant structure, which was not considered in the model formulation.

Keywords: CFD, drag force, vegetation, wildland fire

1. Introduction

An important component in understanding, and therefore modeling, wildland and Wildland-Urban Interface (WUI) fire behavior is the fluid-structure interaction induced by vegetation drag. Even for simple porous natural fuels, it is well established that the effect of the fuel structure on the flow plays a role in determining fire behavior (Thomas, 1963; Anderson, 1969). It follows

that this is also the case for more complex real vegetation. As modeling capabilities improve and increasing focus is placed on tools that can reproduce complex three-dimensional vegetation structures (Marcozzi et al., 2025), it is imperative that fire models can capture these interactions. For example, this has been highlighted in computational studies that simulate the effects of fuel treatment measures or disturbance events on vegetation structure and show the modification to drag forces changes fire behavior (e.g. Pimont et al., 2011; Hoffman et al., 2015). However, further work is required to evaluate and refine the submodels used to represent vegetation drag.

Drag in vegetation has been the subject of many studies in the past, covering a wide range of topics. These include tree damage in extreme wind conditions (Cullen, 2005), the effect of aquatic vegetation in water quality and erosion (Nepf, 2012), and the role of forest canopies on the turbulent boundary layer and subsequent effects on processes such as carbon exchange or seed dispersal (Raupach and Thom, 1981; Finnigan, 2000). In these contexts, vegetation is typically treated as a single object (e.g. a tree) or a continuous layer of porous media (e.g. a forest canopy). This choice is dictated by the scale of the problem as well as the the type of model which might be applied to understand it.

In the case of individual trees or shrubs, proposed drag coefficients typically relate a net force to a free stream velocity using a characterization of total plant frontal area. There are numerous such examples for both real trees (e.g. Lai, 1955; Mayhead, 1973; Grant and Nickling, 1998; Vollsinger et al., 2005; Ishikawa et al., 2006; Angelou et al., 2021; Falkenstein-Smith and McGrattan, 2021) and surrogate trees (e.g. Guan et al., 2003; Gromke and Ruck, 2008). Drag in these cases is often obtained with a direct force measurement, though pressure (Falkenstein-Smith and McGrattan, 2021) and velocity (Angelou et al., 2021) deficit techniques have also been used. While empirical coefficients vary across specimens, an important finding with real trees is that changes in structure/frontal area with increasing speed (streamlining due to flexibility) will affect the total drag force (Rudnicki et al., 2004; Vollsinger et al., 2005; Ishikawa et al., 2006). Another interesting factor is the non-trivial relationship between optical porosity (related to imaging frontal area of the whole plant) and true volumetric porosity (Grant and Nickling, 1998; Guan et al., 2003). This highlights the potential issues in characterizing plant structure with a simple measurement like frontal area and the difficulty in comparing derived coefficients or applying them to various modeling approaches.

Similarly, there are many examples of drag characterization for more homogeneous vegetative canopies, both in field studies (Amiro, 1990; Gillies et al., 2002; Shaw and Patton, 2003) and in the laboratory (e.g. Tanino and Nepf, 2008; Pan et al., 2016; Mueller et al., 2021). In this case velocity or pressure deficit measurements are more typical. Drag coefficients are related to local interstitial velocity and plant area density (or projected area per unit volume) distributed throughout the canopy.

In the context of computational fluid dynamics (CFD) models of wildland fires, some work has been done to assess typical model formulations against quasi-homogeneous canopy-type fuels. In order to reproduce the physics of heat and mass transfer that drive fire spread, these models require a description of plant element (e.g. leaf) geometry and packing throughout the canopy. Thus the connection to plant area density and past measurements of canopy flows is relatively straightforward. With proper tuning, these models can reproduce bulk flows in large scale forest canopies (Pimont et al., 2009; Mueller et al., 2014) down to small scale litter layers (Mueller et al., 2021). However, little work has been done to assess predictions from CFD fire models with respect to individual tree or shrub studies where direct drag force measurements were made.

To understand the difficulty in evaluating these models with previous experiments of single plants, it is helpful to explore the drag force formulation. Typically, within the gas-phase of the CFD model a volumetric drag force, f , is applied in grid cells which contain vegetation. This vegetation may locally consist of many subgrid-scale particles, each of which experiences a force in direction i , F_i , based on a drag coefficient, c_d , and the particle area projected normal to the flow, $A_{p,i}$

$$F_i = \frac{1}{2} c_d A_{p,i} \rho u_i |\mathbf{u}| \quad (1)$$

The volumetric contribution of N such identically sized particles in the grid cell volume, V_c , is then

$$f_i = \sum_{n=1}^N \frac{F_{n,i}}{V_c} = \frac{1}{2} c_s c_d \sigma \beta \rho u_i |\mathbf{u}| \quad (2)$$

The product of the surface-to-volume ratio, σ , and the packing ratio (or solid volume fraction), β , gives the total particle surface area per grid volume. The shape factor, c_s , relates this surface area to a projected area in the direction of the flow. The integral force experienced by the entire plant, which may

contain M different types or classes of particles, would then be

$$F_{d,i} = \int_V \left[\sum_{m=1}^M \frac{1}{2} c_{d,m} c_{s,m} \rho \sigma_m \beta_m u_i |\mathbf{u}| \right] dV \quad (3)$$

Each constituent class may be characterized by its own drag coefficient, shape factor, surface-to-volume ratio, and packing ratio. Decomposing the vegetation into such different classes may be important for modeling fire behavior, particularly if different sizes lead to different thermal responses (Mell et al., 2009; Finney et al., 2013). This type of approach can be found in a number of different CFD wildland fire models (e.g. Linn et al., 2002; Morvan et al., 2018; Ahmed et al., 2022; McGrattan et al., 2025)

We are not aware of past studies which provide both drag measurements of isolated vegetation structures *and* a level of structural characterization sufficient to parameterize and evaluate this drag modeling approach. Using a small scale wind tunnel and direct drag force measurement, this study is intended to help fill this gap. We systematically increased the complexity in representative vegetation structures. First we tested an array of screens, creating a kind of porous media where all parameters in Equation 3 can be reasonably obtained. Next we tested a series of idealized vegetation structures constructed with excelsior (wood wool) fibers. This material allows control over the packing ratio while allowing exploration of the assumptions applied to other model parameters. It is also a relevant test material in the wildland fire literature (Catchpole et al., 1998; Marchand et al., 2019; Mueller et al., 2025). Finally, we tested branches (including foliage) of real vegetation, which present the greatest challenge for model parameterization. Experimental observations are contrasted with numerical simulations

2. Methods

2.1. Wind tunnel measurements

Drag measurements were made by placing vegetation samples in the test section of a 0.5 m by 0.5 m wind tunnel, which has been described in Falkenstein-Smith and McGrattan (2021) and Di Cristina and Bryant (2024). A schematic of the tunnel and the measurement configuration is shown in Figure 1

Upstream velocity was measured with a series of eight pitot tubes at the test section inlet, with a vertical spacing of 6 cm starting 4 cm from the tunnel

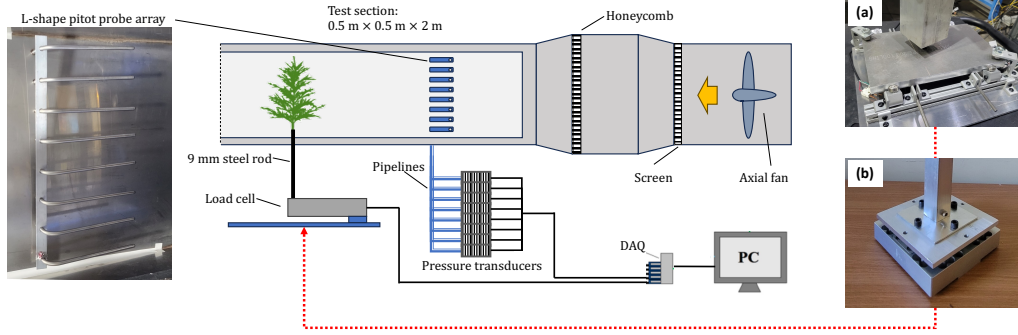


Figure 1: Layout of wind tunnel showing sample location and instrumentation. Two force measuring assemblies were used: (a) a custom made, nearly-frictionless platform and (b) a commercial 3D force measurement device.

floor. Pressure values were recorded with differential transducers (range: ± 0.1 inch.w.c.) and converted to velocities using the Bernoulli equation and a manufacturer-specified calibration factor. Measurements were recorded at 1 Hz. In this work, test velocities ranged between approximately 1 m s^{-1} and 8 m s^{-1} .

In a subset of experiments, the pitot probe array was used to measure the flow profile downstream of a sample. In this case the probe tips were a distance of 36 cm downstream of the sample center and the vertical array was traversed to successive spanwise positions to create a grid of measurements. The spanwise grid matched the vertical, in that positions were spaced by 6 cm starting 4 cm from the wall.

Two methods were employed for obtaining direct drag force measurements, as shown in Figure 1. The first was a frictionless table assembly which transferred horizontal force to a load cell with a pin connection. The second was a commercial three-dimensional force measurement assembly. Both methods were calibrated with standard weights and produced comparable results. However, the 3D force sensor was favored in later tests, as the bearings in the frictionless assembly introduced hysteresis that required repeated zeroing in between test conditions.

2.2. Screen drag

As mentioned in the Introduction, the first series of tests used wire screens to create a discrete porous object with element size comparable to vegetation foliage. These screens were 18 cm by 18 cm in area and had a wire diameter of 0.71 mm and a free area fraction of 78 %. Four configurations of screens were used, as summarized in Figure 2. The screens were attached to the force measurement system with a single central support which was 1 cm in diameter. The estimated force from this support alone was subtracted from the screen drag; however, it contributed less than 6 % of the total force (with a diminishing contribution for two- and three-screen configurations).

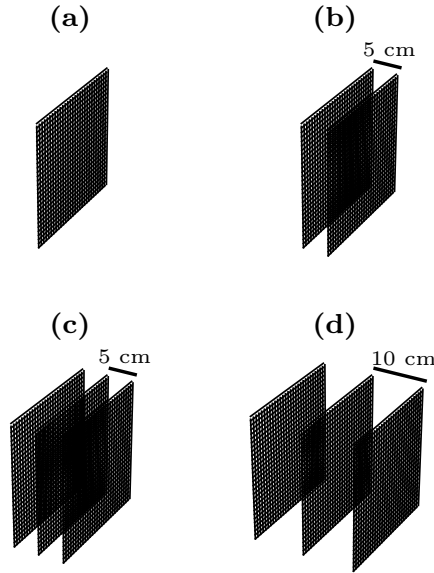


Figure 2: Four combinations of 18 cm by 18 cm screens tested in the wind tunnel.

2.3. Vegetation drag

Following the evaluation of screen drag, we measured both idealized and real vegetation samples. The idealized vegetation was comprised of excelsior (*Populus tremuloides*) wood fibers wound around a 6.35 mm (0.25 in) support rod with tines. This configuration resembled that reported in related work on the burning behavior of excelsior ?Mueller et al. (2025). These samples were nominally 30 cm in length with a diameter of 15 cm. Two sample bulk

densities, or porosities, were tested: a ‘low density’ sample with 30 g of excelsior and a ‘high density’ sample with 75 g of excelsior. Three repeat tests were conducted for each bulk density. An image of a sample specimen is shown in Figure 4a.

In addition to the idealized vegetation samples, we tested a series of samples from real vegetation. In this case we used branches of Douglas fir (*Pseudotsuga menziesii*) and eastern white pine (*Pinus strobus*). These branches were trimmed to fit within the wind tunnel section and so had lengths on the order of 30 cm to 40 cm. They were attached to the force measurement system via a single vertical support at the base of the branch. As with the idealized vegetation, the exact mass, volume, and particle distribution were characterized for each sample. Images of example specimens are shown in Figure 4.

2.3.1. Vegetation element geometry

The characteristic geometry of different elements of the vegetation, i.e. foliage or branches, was determined through a combination of image analysis and physical measurement. Samples were deconstructed into particle segments and images were taken against an illuminated background. Standard post-processing routines were used to binarize the images, identify individual particles, skeletonize the particles to obtain length, and compute the shortest Euclidean distance from points along the skeleton to the particle edge in order to obtain width (or diameter). This allowed many measurements to be made along the length of the particle with minimal effort compared to physical measurement. Length and width were converted from pixels to physical dimensions using a calibrated reference image. An example of this process is shown in Figure 3a-b.

For approximately cylindrical particles, such as branches and excelsior fibers, the average surface-to-volume ratio was calculated from the mean particle diameter as $\sigma = 4/d$. The mean particle diameter was determined from the length-weighted cumulative distribution, as shown in Figure 3c. Excelsior fibers and white pine branches had diameters in a relatively narrow range that could be characterized by a mean value. The primary branch of the Douglas fir (referred to here as a ‘stem’ for clarity) was significantly larger than secondary branches with foliage, leading to a bimodal distribution. For this reason, Douglas fir branches were characterized in two size classes. Finally, Douglas fir and white pine foliage do not necessarily resemble cylinders and so literature values which consider fine details of the geometry

were used (Brown and Davis, 1973; Thomas et al., 2017). A summary of particle surface-to-volume ratio for each sample is given in Table 1

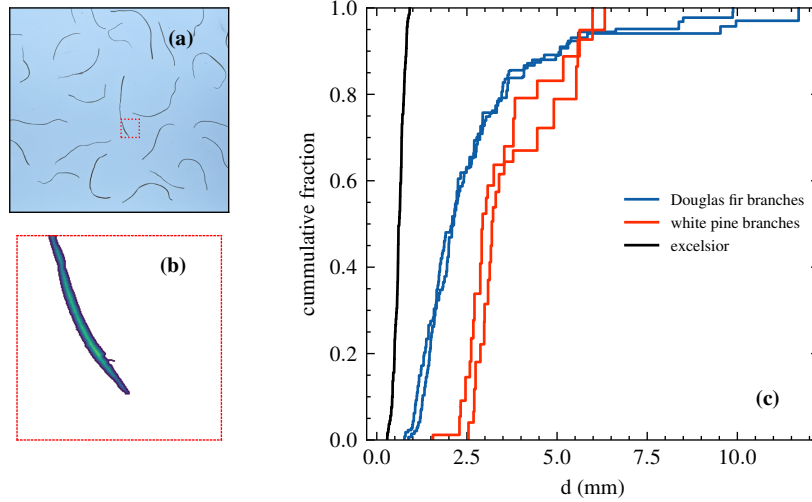


Figure 3: Particle size analysis. (a) An example of a raw image – in this case excelsior fibers. (b) The segmented particles, colored by pixel distance to particle edge (width), for the region highlighted in (a). (c) cumulative distribution function (CDF) of length-weighted diameter of particles used to determine surface-to-volume ratio of excelsior and real vegetation branches.

2.3.2. Vegetation solid volume

For the idealized vegetation (excelsior) the total solid volume was determined from the fiber density. The sample mass of excelsior was converted to a dry mass using an average measured moisture content of 6 % and then to a volume using a dry material density of 400 kg m^{-3} (Catchpole et al., 1998).

For the real vegetation samples the total solid volume of vegetation samples was determined with a water-displacement technique, similar to Falkenstein-Smith and McGrattan (2021). Samples were separated into foliage and branches, based on the categories identified in Table 1, and the displacement volume was measured by placing the vegetation into graduated cylinders which were filled with water and placed on a load cell.

2.3.3. Vegetation bounding volume

In order to determine a packing ratio, as well as a bounding three-dimensional shape to be input into the CFD model, a visual hull pho-

Table 1: Particle surface-to-volume ratio for each sample tested. EX refers to excelsior (all samples were assumed to have the same properties), DF refers to Douglas fir, and WP refers to white pine. Combined expanded uncertainties are determined following the calculation discussed in Appendix A.

sample	foliage σ (m^{-1})	branch σ (m^{-1})	stem σ (m^{-1})
EX ¹	6460 ± 260	–	–
DF	6910 ± 730^2	1870 ± 110	520 ± 70
WP	$14\,170 \pm 460^3$	1100 ± 110	–

¹All excelsior samples are assumed to have the same particle characteristics

²Brown (1970)

³Thomas et al. (2017)

togrammetry technique was employed following Phattaralerphong and Sinoquet (2005). In this method, a voxelized representation of a complex three-dimensional volume, such as a tree crown, is created from a series of photos at different angles. Here, 12 photos were taken of the sample outside of the wind tunnel, covering a full 360 degree rotation at angular increments of 30 degrees. Each image was binarized to isolate the vegetation from the background and then sub-sampled based on 10 by 10 groupings of pixels, with the macropixel getting a value of 1 if more than 50 % of constituent pixels contained vegetation. The scale of the pixels (and the corresponding distance between the camera and the object) was determined using a known calibration grid. A three-dimensional mesh was created based on a predetermined resolution. This could be set to any resolution up to that of the CFD domain. A ray-tracing algorithm was then employed to determine the intersection of rays which correspond to vegetation containing macropixels with the mesh grid. Each new image angle allows successive refinement of the vegetation containing volume. Examples of the vegetation specimens with corresponding bounding volumes obtained with this subtractive hull method are given in Figure 4.

The results of the physical characterization of the idealized excelsior vegetation are shown in Table 2. The bounding volumes were determined using a 1.25 cm voxel size, matching the numerical grid. This volume, and thus the bulk density, depends on the choice of voxel size but is not strongly dependent owing to the simple geometry of the cylindrical excelsior bundles. Therefore, we explored the effect of voxel size in the context of the real vegetation samples where the impact is more pronounced.

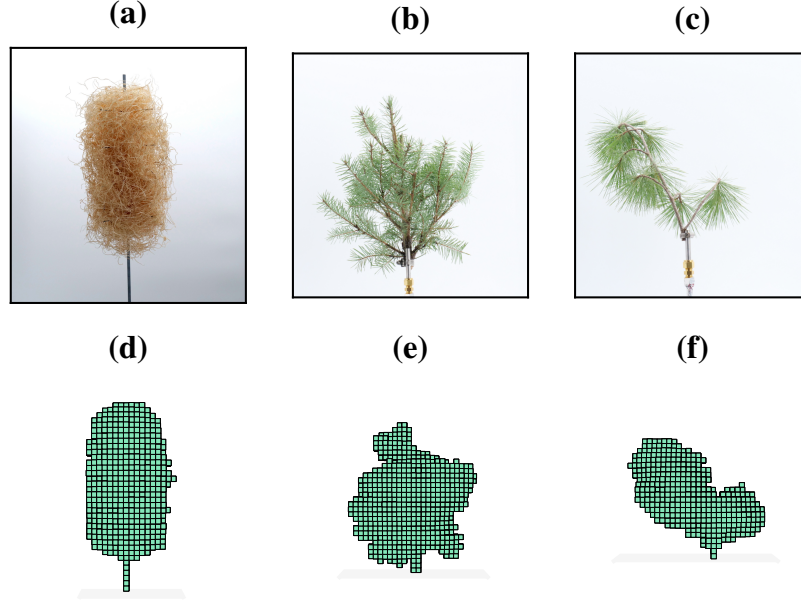


Figure 4: Examples of (a) excelsior, (b) Douglas fir, and (c) white pine. The bounding volumes shown in (d-f) were obtained using a 1.25 cm voxel size, following the method in Section 2.3.3.

Table 2: Geometric properties of idealized excelsior (EX) vegetation samples. These include mass, m , bounding volume, V_b , bulk density, ρ_b , and packing ratio, β . Samples are classified as either high (EX_H) or low (EX_L) bulk density. Combined expanded uncertainties are determined following the calculation discussed in Appendix A. Expanded uncertainty in the mass was less than 0.1 g.

	EX_H_1	EX_H_2	EX_H_3
m (g)	77.3	76.4	75.3
V_b (m ³)	$(1.050 \pm 0.030) \times 10^{-2}$	$(8.80 \pm 0.27) \times 10^{-3}$	$(1.105 \pm 0.030) \times 10^{-2}$
ρ_b (kg m ⁻³)	7.36	8.68	6.81
β (-)	0.017 ± 0.002	0.020 ± 0.002	0.016 ± 0.002
	EX_L_1	EX_L_2	EX_L_3
m (g)	30.4	31.3	30.4
V_b (m ³)	$(6.30 \pm 0.25) \times 10^{-3}$	$(7.02 \pm 0.25) \times 10^{-3}$	$(8.05 \pm 0.27) \times 10^{-3}$
ρ_b (kg m ⁻³)	4.83	4.35	3.58
β (-)	0.011 ± 0.001	0.010 ± 0.001	0.008 ± 0.001

The characteristic physical properties of the real vegetation samples are shown in Table 3. The Douglas fir samples were larger overall (in both mass and total volume) but had a lower percentage of foliage volume (42 % on average) compared to the white pine (71 % on average). The Douglas fir branches also had a larger central stem which was treated separately from the smaller branches, as described in Section 2.3.1.

Estimates of bounding volumes for the vegetation, as well as the corresponding packing ratio for each class, are also provided in Table 3. Unlike the excelsior, the complex shape of the real vegetation specimens means that the resolution of the voxelized vegetation volume may play a significant role, independent of the CFD resolution. The coarsest logical resolution is that of a bounding box which contains the full extent of the vegetation in each principle axis. The volume is then refined with the subtractive hull method to both a 5 cm and 1.25 cm grid.

Table 3: Properties of Douglas fir (DF) and white pine (WP) vegetation samples. These include mass, m , foliage solid volume, V_{fo} , branch solid volume, V_{br} , stem solid volume, V_{st} , and bounding volume, V_b . Combined expanded uncertainties are determined following the calculation discussed in Appendix A. Expanded uncertainty in the mass was less than 0.1 g.

	DF_1	DF_2	DF_3
m (g)	49.9	88.4	63.1
V_{fo} (cm ³)	43 ± 2	69 ± 2	51 ± 2
V_{br} (cm ³)	29 ± 2	33 ± 2	41 ± 2
V_{st} (cm ³)	32 ± 2	61 ± 2	26 ± 2
V_b (m ³)	$(1.275 \pm 0.017) \times 10^{-2}$	$(2.619 \pm 0.022) \times 10^{-2}$	$(1.446 \pm 0.019) \times 10^{-2}$
	WP_1	WP_2	
m (g)	18.2	16.0	
V_{fo} (cm ³)	37 ± 2	31 ± 2	
V_{br} (cm ³)	12 ± 2	15 ± 2	
V_b (m ³)	$(7.95 \pm 0.14) \times 10^{-3}$	$(1.023 \pm 0.018) \times 10^{-2}$	

2.3.4. Vegetation frontal area

In-situ plant frontal area was also measured, in particular to characterize the potential for streamlining of the flexible vegetation. This measurement was obtained with a camera positioned upwind of the wind tunnel test section at the level of the test section floor. The vegetation sample was back-lit so

that a binary image could be extracted from a threshold applied to a grayscale image. Pixel count was converted to area through the use of a calibration grid at the location of the object. This also allowed re-projection of the image to account for perspective distortion. An example is given in Figure 5. For each test condition, several seconds of footage was captured so that an average frontal area could be calculated, accounting for the fluttering of individual elements which could affect the instantaneous estimate of frontal area.



Figure 5: Example of in-situ frontal area measurement for a Douglas fir branch. (left) Single frame from video. (right) Binary image corrected for perspective distortion.

2.4. Numerical modeling

The experiments were simulated using the Fire Dynamics Simulator (FDS) in order to determine an effective drag coefficient for each sample. This is a large eddy simulation (LES) CFD model which makes use of a low-Mach number formulation. A full description of the mathematical formulation is given in McGrattan et al. (2025). It is used to model a range of different fire phenomena. Among these are scenarios related to wildland and wildland-urban interface fires (e.g. Mell et al., 2009; Mueller et al., 2021, 2023), which require modeling of the drag associated with flow through the vegetation. A typical approach is to treat the vegetation as a highly dispersed porous medium, and this allows the application of Equation 3 for modeling these experiments to be tested. Similar approaches are taken in other models (Pimont et al., 2009; Morvan et al., 2018; Ahmed et al., 2022, e.g.), so the findings are relevant beyond FDS.

2.4.1. Drag model parameterization

A key component of this work is the parameterization of Equation 3. For the screen tests, the wires were treated as a collection of cylinders perpen-

dicular to the flow with diameter d . This leads to $\sigma = 4/d$, $c_s = 1/\pi$, and β was set from the number of wire elements that are within a given grid cell of the model. The drag coefficient used an empirical expression based on the Reynolds number, $Re = \sigma u/\nu$ (Schlichting and Gersten, 2016)

$$c_d = \begin{cases} \frac{10}{Re^{0.8}} & Re \leq 1 \\ \frac{10}{Re}(0.6 + 0.4 Re^{0.8}) & 1 < Re < 1000 \\ 1.0 & Re \geq 1000 \end{cases} \quad (4)$$

In the case of the vegetation (idealized and real), bulk volume was determined following the method outlined in Section 2.3.3, with the packing ratio based on this volume and the solid volume following Section 2.3.2. The surface-to-volume ratio was obtained following Section 2.3.1. For samples comprised of multiple particle classes, each was assumed to be distributed uniformly throughout the bulk volume. This may be a reasonable approximation for foliage and secondary branches, but is not representative of a primary branch/stem. However, due to the combination of a small packing ratio and small surface-to-volume ratio, the contribution to the drag from the trunk is comparatively small and so the errors are reduced.

An additional simplification is the assumption that all particles have a drag coefficient following Equation 4 and that they are uniformly randomly orientated ($c_s = 1/4$). As with the volume distribution, this assumption of statistical isotropy becomes less justified as we move from idealized to real vegetation. The implications of this assumption are discussed below along with the results.

2.4.2. Model domain

The wind tunnel was represented in the model by a rectangular duct of 2.0 m by 0.5 m by 0.5 m. The upstream ($x = 0$ m) boundary was set to a range of fixed velocities based on the experimental test conditions, and each condition was held for 10 s to ensure steady conditions. The downstream boundary was assumed to be at ambient pressure. The sidewalls employed a log law wall model to represent the unresolved boundary layer. The target of interest (screen or vegetation sample) was centered at $x = 1.0$ m downstream from the inlet in order to limit interaction with either the upstream or downstream numerical boundaries. The baseline numerical resolution was 1.25 cm by 1.25 cm by 1.25 cm. An example of the simulated domain with an excelsior sample is shown in Figure 6.

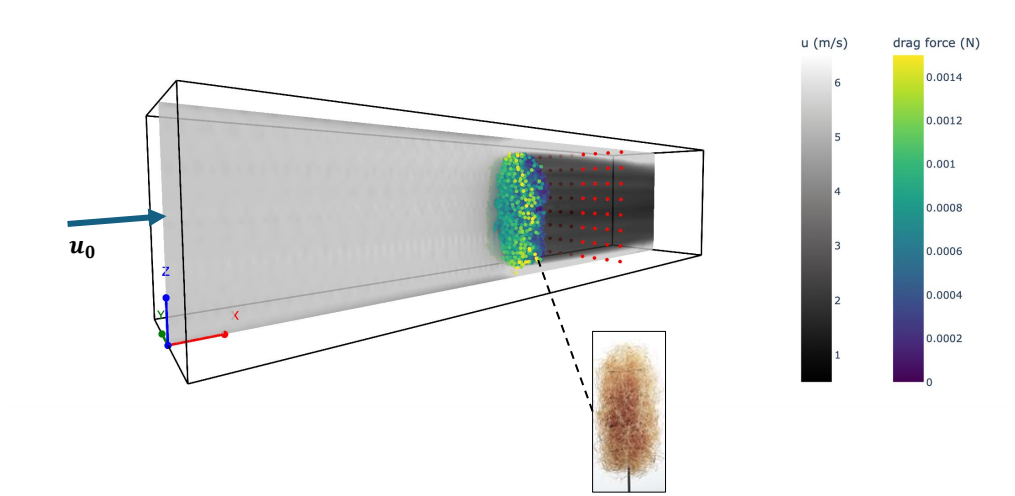


Figure 6: Example of simulated wind tunnel domain (sample EX6). Free-stream velocity, u_0 , is prescribed at the upstream boundary. A slice of u velocity is shown along the vertical central plane. Colored particles represent grid cells which contain porous vegetation, with the color representing the local drag force. The grid of red dots shows the location of downstream velocity measurements.

3. Results

3.1. Screens

The results of the screen drag experiments and modeling are shown in Figure 7. This reveals that the numerical approach of representing the screen as a collection of independent cylindrical elements, perpendicular to the flow, reasonably reproduces the measured magnitude of the total force on the screens, with a slight tendency towards under-prediction. The average error in prediction over all cases was 13 %, reducing to 8 % if the lowest velocity point (with the highest relative error but absolute values close to zero) is excluded.

The ratio of the force for multiple screens to that of a single screen is shown in Figure 7b. The simulation does not match the experimental ratio well for the lowest velocity, but here the forces are very small and measurement error can significantly affect the ratio. However, as velocity increases the experiments and simulations converge to the same ratios for both two and three screens. Of note is the fact that the ratio appears to converge to about 1.8 and 2.5 for the two- and three-screen configurations, respectively. Thus the contributions of additional screens are not purely additive in force. For this discrete ‘object’ immersed in the flow, there is a sheltering effect with a flow deceleration through the screens and a corresponding acceleration of the flow in the free space around them. The reduced velocity seen by downstream screens explains this less than additive effect. The fact that the model captures these effects and reproduces the measured drag indicates that, for simple objects, the approximated local drag from subgrid particles can be applied to represent the effect of the bulk porous object on the flow field.

3.2. Idealized vegetation

Figure 8a compares the measured drag force for all excelsior samples with the integrated force from the simulations, separated by nominally ‘low’ and ‘high’ bulk density/packing ratio. Low samples had an average $\beta = 0.01$ and high density had $\beta = 0.018$. The randomly oriented cylinder model for the drag appears to be a reasonable approximation for this idealized structure. There was a slight tendency for the model to over-predict the total force, with an average error of 12 % when comparing results for individual specimens. The model qualitatively captures the difference between low and high bulk density samples.

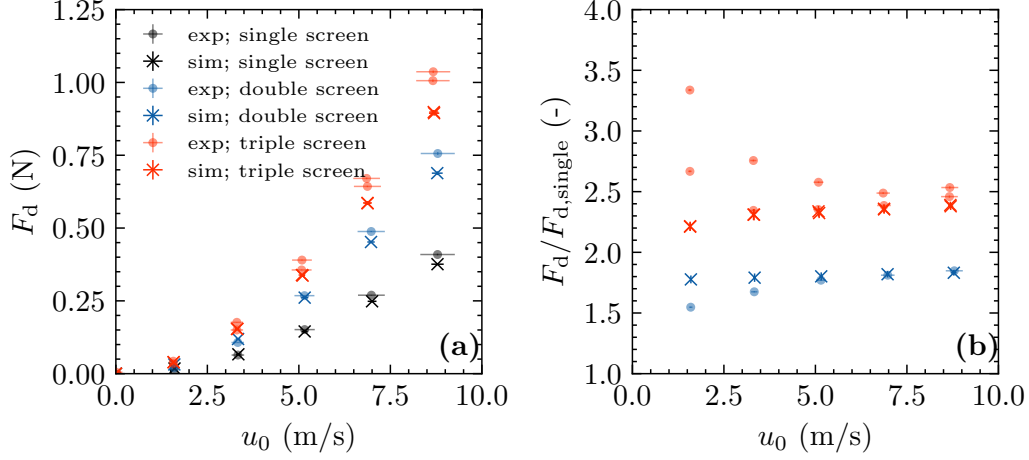


Figure 7: (a) Comparison of measured and modeled drag force for one, two, and three screens in series, and (b) ratio of two- and three-screen force to single screen. Note that the three screen configuration includes two different spacings. Experimental error bars represent a combined expanded uncertainty as described in Appendix A and simulation error bars represent two standard deviations in the mean.

Figure 8(b) further highlights the role of bulk density in the simulation. In this case, a single sample geometry was selected (EX6) and the bulk density was artificially varied. Examining two different free-stream velocities, one can see an apparent non-linearity in the dependence of the total force on bulk density, despite the linear form of β in Equation 3. This result highlights the connection between the local force model and the integrated force over the entire immersed 3D vegetation structure, via the variation in local velocity used in Equation 3. While the qualitative reproduction of the effect of bulk density in Figure 8(a) is encouraging, this only represents two nominal bulk densities, and this may be an aspect for more detailed investigation in future work.

Another way to interrogate the quality of the drag force predictions is through the velocity field in the wake of the specimen. This is particularly important if the aim of this model is to predict the burning dynamics of vegetation, which is driven by the characteristics of the flow field.

Figure 9(a) shows the velocity field obtained from the array of pitot probe measurements at a distance of 36 cm from the center of sample EX6. This is compared to the analogous simulated velocity profile in Figure 9(b). In

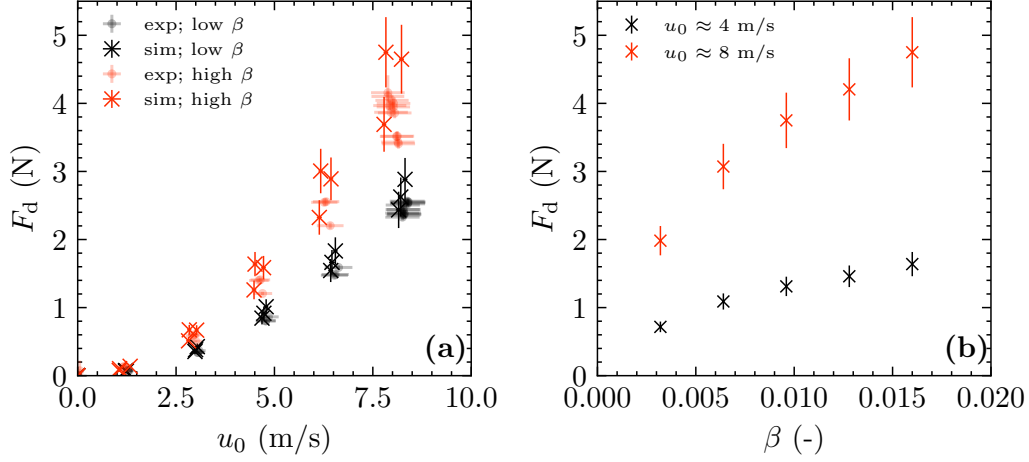


Figure 8: (a) Combined experimental and simulation results of drag force for excelsior vegetation, separated into low and high packing ratio, β . Low samples had an average $\beta = 0.01$ and high density had $\beta = 0.018$. (b) Model results for one sample (EX6) with a range of modified bulk densities at two free-stream velocities. Error bars represent a combined expanded uncertainty as explained in Appendix A.

both cases, the velocity is normalized against the mean free-stream velocity in order to highlight the relative effect. For a more quantitative comparison a horizontal profile of the normalized velocity is extracted near the tunnel midplane height and shown in Figure 9(c).

The experiment and model showed similar velocity deficits in the sheltered wake region ($u/u_0 < 1$), though this was slightly more pronounced in the experiment—the minimum value was 0.02 for a free-stream velocity of 4 m s^{-1} , compared to 0.18 in the simulation. Both results also show an acceleration of the flow around the object, which is likely influenced by the confinement within the wind tunnel. Across the whole flow field, the average error in predicted normalized velocity is 11 %, regardless of the magnitude of the free-stream velocity. Notably, both the experiments and simulation showed that the relative change in velocity was essentially independent of its magnitude.

The measured velocity profile was somewhat limited by spatial resolution, with a spacing of 6 cm. It is not clear whether the gradient between the wake region and the surrounding flow is as steep as the model predicts. However, given that the model does not include any of the local variation in the real

sample (e.g. the potential for diminishing bulk density near the outer surface of the sample), the results are encouraging. Future work will expand this investigation to include variations in bulk density as well as additional flow characterization as a function of downstream location. This will provide better insight into the spatial extent of the sheltering effect and whether the normalized flow field remains velocity-invariant further downstream.

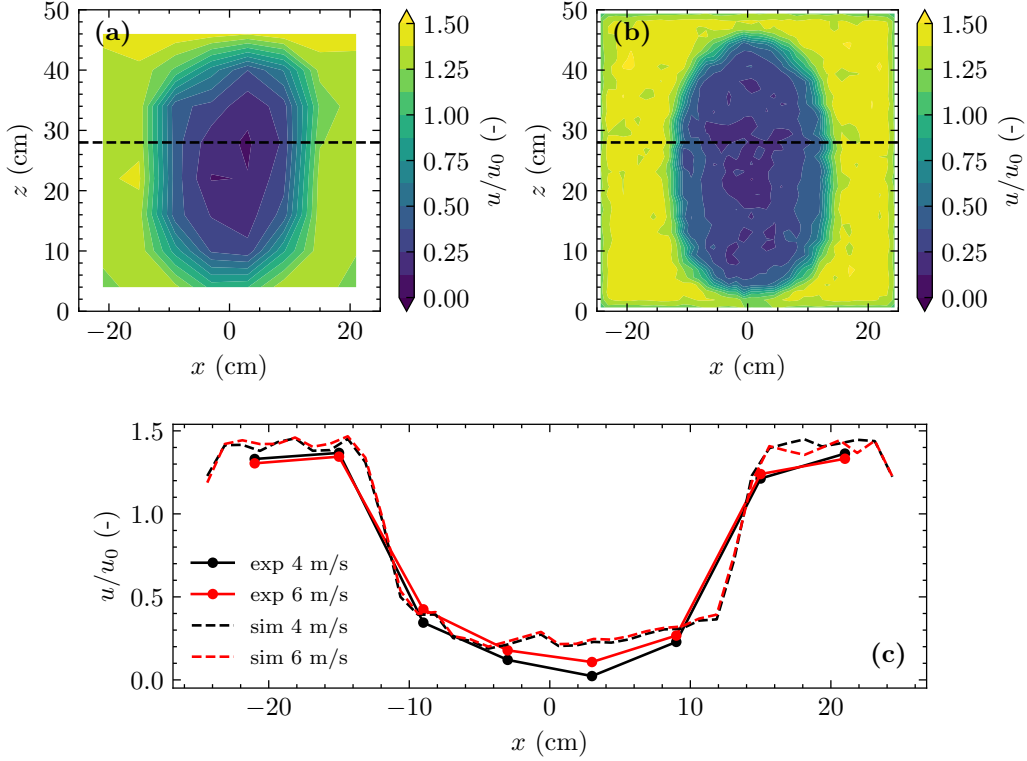


Figure 9: (a) Experiment and (b) simulation velocity fields downstream of high packing ratio excelsior specimen ($\beta = 0.016$) for a nominal free-stream velocity of $u_0 = 6 \text{ m s}^{-1}$. (c) Linear profile of velocity near the tunnel midplane, as shown by the dashed line in (a) and (b), for two different free-stream velocities. All velocity values are normalized to the free-stream value.

3.3. Real vegetation

Figure 10 shows the measured and predicted drag forces for all samples, separated by plant species. The experiment showed a clear difference in drag

as a function of species, with an average maximum force of about 3 N for Douglas fir samples compared to about 1 N for white pine (both at about 8 m s^{-1}). On the other hand, the differences in the simulations were less significant and there was a tendency for over-prediction. For Douglas fir the average error was 21 % and for white pine it was 189 %. For both species, except sample DF2, the experimental observations fall outside the expanded uncertainty bounds for the simulations. This suggests the discrepancy did not originate from uncertainty in the characterization of σ or β . For β this is supported by the fact that, for a given species, the model reproduced the trend in force as a function of individual specimen. This demonstrates the relative success in the characterization of volume and packing ratio.

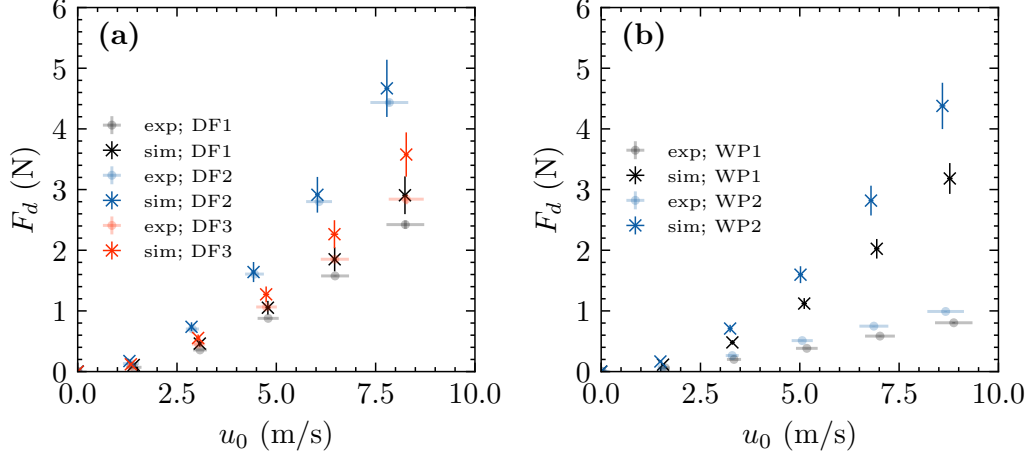


Figure 10: Experimental and simulated total drag force for (a) Douglas fir samples and (b) white pine samples. Each color represents a specific sample (with geometric characteristics reproduced in the simulation). Error bars represent a combined expanded uncertainty following Appendix A

The discrepancy in force is then likely related to assumptions or simplifications around the factors c_s and c_d in Equation 3. As noted in Section 2.4.1, the initial assumptions did not deviate from that of randomly oriented cylinders. To evaluate this choice, we ran an additional set of simulations with $c_s c_d = 1$. The predictions from these simulations were normalized by the experimental data in order to give an empirical factor which would produce a better match. This factor was a function of velocity, and Figure 11(a) presents it as a function of Reynolds number of the foliage. In reality, these

specimens have multiple particle sizes and the corrective factor may need to be tuned individually. However, as we only have integrated force data from all particles, and the foliage provides the majority of projected area. Thus, a single correction based on foliage Reynolds number is applied as a first approximation. This was confirmed by repeating the simulation of DF3 with the corrected model of $c_s c_d$. The average error of total drag was reduced from 26 % to 6 %. When excluding the lowest velocity set point (which had the highest relative error), the average error in the corrected model was less than 1 %. As expected, when compared to the random cylinder model, both corrected factors have a smaller value. The Douglas fir requires a smaller correction and the Reynolds-dependence more closely matches the cylinder model. The white pine appears to depend more strongly on Reynolds number.

To evaluate these effects, Figure 11(b) shows the frontal area based on video footage of each sample. In both cases, some streamlining occurred with increasing velocity, as the branches and foliage bent relative to the applied force. This effect is less pronounced for the Douglas fir, where the average area of the specimens at the highest velocity was 81 % of the area in still air. On the other hand, white pine has long flexible needles and the velocity reduced to an average of 53 % of the still area value. This dynamic behavior is reflected in the empirical corrections of Figure 11(a).

4. Discussion

A key question related to this work is how generalizable the findings are. In other words, to what extent is it necessary to measure and obtain specific model parameters for the wide range of vegetation structures which can be found in reality. When testing this modeling approach for continuous beds of pine needle litter, Mueller et al. (2021) found that the random cylinder model for $c_s c_d$ need to be reduced by an average of 36 % to produce the best results. This finding is in line with the over-prediction of drag in excelsior in this excelsior study, though to a smaller extent. Thus, while some tuning may be required, the typical approach appears generally applicable to assemblies of thin particles which are nominally uniform in size and do not have strong anisotropy in orientation.

On the other hand, it is clear from these results that important aspects of more complex plant structure, such as flexibility, are only empirically included in Equation 3. The approach of modifying the velocity-dependence of

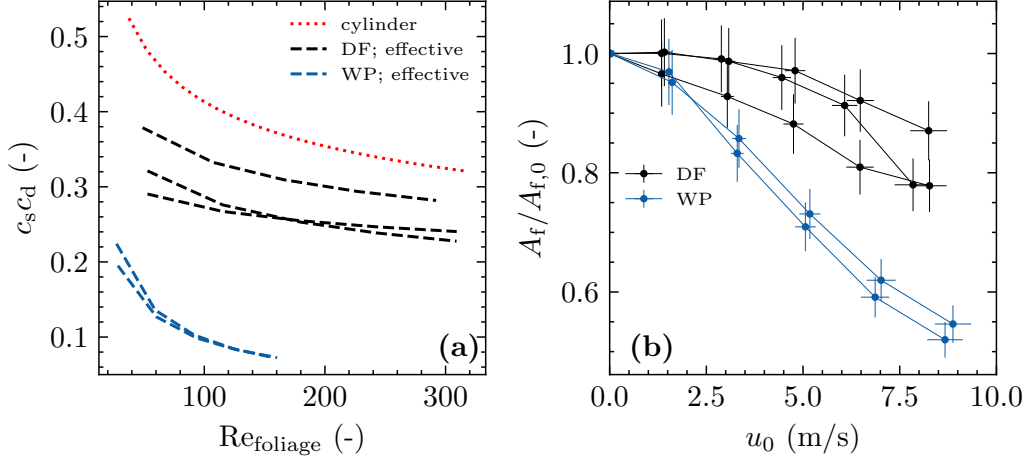


Figure 11: (a) Proposed empirical factor $c_s c_d$ based on corrected numerical predictions. The factor for randomly oriented cylinders is included for comparison. (b) Change in total plant frontal area, A_f , relative to the value in still air, $A_{f,0}$. Error bars represent a combined expanded uncertainty following Appendix A.

the drag coefficient to compensate for departures from still-air geometry has been applied in other work (e.g. Rudnicki et al., 2004). However, the effects of the geometry changes on heat transfer, for example by locally compacting vegetation, would not be included in such an empirical correction.

In summary, the model performance is closely tied to how well it has been parameterized for a given type of vegetation. As discussed in the introduction, many prior studies characterize plant drag in a way which yields coefficients based on total frontal area. These are not directly applicable to the three-dimensional porous media approach used for modeling vegetation fires. An investigation by Falkenstein-Smith and McGrattan (2021) aimed to characterize drag as a function of a light attenuation factor, $c_s \sigma \beta$, rather than A_f . They suggested an average drag coefficient of $c_d = 2.8$, which would substantially over-predict the forces observed here. However, σ was not measured directly. Inferring a value from the reported values of β and a shape factor of 0.25 suggests the attenuation factor may have been under-predicted. For example, a blue spruce sample with a total packing ratio of 0.019 had an attenuation coefficient of around 2.7 m^{-1} . This would suggest an volume averaged surface-to-volume ratio of 570 m^{-1} . Given the reported branch/foilage ratio was 1.1 and that spruce foliage has been reported to have a surface-

to-volume ratio in excess of 5000 m^{-1} (Brown, 1970), this would suggest an underestimation of the attenuation coefficient. This could then explain an over-estimation of c_d . Alternatively, if the attenuation factor is correct the real shape factor may be smaller than 0.25, leading to the same result of a larger drag coefficient compared to the results here. The latter would suggest some anisotropy that would need to be considered in other components of a fire model. Regardless, this further highlights the difficulty in applying literature values of drag coefficients when this factor is so strongly dependent on how the geometry of the specimen is defined and measured. While the current approach of separately characterizing σ and β is more labor intensive, it is relevant for fire modeling, where these parameters play roles in several processes, such as radiative and convective heat transfer.

5. Conclusions

In this work we present a comparison between measurement and CFD modeling of drag in porous structures, representative of vegetation, in the context of wildland fire modeling. The results of this analysis demonstrates that the approach of modeling vegetative drag using subgrid Lagrangian particles—tending towards a dispersed porous media formulation—has the potential to capture macroscopic features of the complexities of fluid-vegetation interaction. This is particularly true for simple structures which are more readily characterized (e.g. uniform particle sizes with ordered or uniformly random orientation). In this case, the drag formulation satisfactorily reproduces both total force and wake velocity using *a priori* coefficients. The main challenges arise in the case of complex structures where element orientation and flexibility may have played a significant role, and a *posteriori* tuning was required. Future efforts should strive, at a minimum, to evaluate predictive tendencies for a wider range of vegetative structures in order to help bound fire model uncertainty. Ideally, more detailed models can be leveraged to support such efforts and to explore these structural effects systematically, leading to improved semi-empirical formulations.

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Appendix A Uncertainty analysis

Uncertainties in this analysis are all reported as a combined expanded uncertainty, U_c . This represents a combination of type A and type B uncertainties, and includes a coverage factor of 2 (intended to approximately represent a 95 % confidence interval)

$$U_c = 2\sqrt{u_{\text{typeA}}^2 + u_{\text{typeB}}^2} \quad (\text{A1})$$

For quantities which involve a calculation with multiple uncertainties, the propagation of errors formula was applied. A full description of sources of uncertainty is given in the subsections below.

A.1 Velocity

The wind flow velocity was measured using the pitot probe array at each fan speed for 30 s, which was typically conducted 1 to 2 times per measurement position. The combined uncertainty in mean velocity was calculated as:

$$u_{c,V} = \sqrt{\frac{s^2}{n} + u_{\text{PT}}^2 + u_{\text{pitot}}^2 + u_{\text{field}}^2} \quad (\text{A2})$$

s is the standard deviation in any repeat tests of the same condition, while u_{field} was obtained from the standard deviation across multiple probes measuring simultaneously.

Table A1: Details of terms in uncertainty of the wind flow velocity

Parameter (x)	Uncertainty, u_x	Descriptions
Pressure transducer (PT)	1 % of full scale	Setra ¹ , Model 264
Pitot tube (pitot)	2 % of full scale	Dwyer, 160-36
Velocity field uniformity (field)	SD of mean velocity	Estimated by measurement

A.2 Force

The drag force acting on a sample was measured using a load cell according to the force measuring assembly. The combined uncertainty in drag force was calculated as:

$$u_{F_d} = \sqrt{\frac{s^2}{n} + u_{\text{loadcell}}^2 + u_{\text{calib}}^2} \quad (\text{A3})$$

where the term (u_{loadcell}) represents the combined uncertainty including nonlinearity, hysteresis, and repeatability. The load cells were calibrated using standard weights, and calibration uncertainty (u_{calib}) was estimated at 0.2 %.

¹Certain equipment, instruments, software, or materials, commercial or non-commercial, are identified in this paper in order to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement of any product or service by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Table A2: Uncertainty of different models by manufacturer

Model	Uncertainty, $u_{loadcell}$
LoadStar, RRP1	0.02 % of full scale
Zhimin, ZM3DW	1 % of full scale

A.3 Frontal area

The average sample frontal area for a given flow condition, as determined by in-situ camera footage, has two main contributions to uncertainty. These are the uncertainty due to selection of a threshold value (between 0 and 1) for binarization of the image, u_{thresh} , and the uncertainty related to the pixel resolution, u_{pixel}

$$u_{A_f} = \sqrt{u_{\text{thresh}}^2 + u_{\text{pixel}}^2} \quad (\text{A4})$$

The threshold uncertainty was estimated by varying the threshold value by $\pm 5\%$, which resulted in an uncertainty of $u_{\text{thresh}} = 0.02A_f$. The contribution from pixel resolution uncertainty was estimated by the number of perimeter pixels on the binary object and the area of a single pixel

$$u_{\text{pixel}} \approx \sqrt{N_{\text{perimeter}}} A_{\text{pixel}} \quad (\text{A5})$$

Due to the relatively high resolution of the images, the contribution from this term ended up being negligible compared to the threshold uncertainty. We also considered the effect of sample fluttering but found the contribution to the calculation of mean area was negligible over the 90 frames considered for each test condition.

A.4 Surface-to-volume ratio

The combined uncertainty in mean surface-to-volume ratio includes contributions from the sample standard deviation, s , and the resolution of the image analysis technique

$$u_{\sigma} = \sqrt{\frac{s^2}{n} + u_{\text{pixel}}^2} \quad (\text{A6})$$

The pixel uncertainty was estimated at $10\mu\text{m}$ leading to uncertainty in surface-to-volume ratio of

$$u_{\text{pixel}} = \frac{1.0 \times 10^{-5}}{\sigma^2} \quad (\text{A7})$$

For values that were taken from literature we only used an estimated sample standard deviation in the calculation of $u_{c,\sigma}$.

A.5 Packing ratio

The calculation of packing ratio has two contributing variables, the solid volume, V_s , and the bounding volume, V_b . This leads to a combined uncertainty

$$u_\beta = \beta \sqrt{\left(\frac{u_{V_s}}{V_s}\right)^2 + \left(\frac{u_{V_b}}{V_b}\right)^2} \quad (\text{A8})$$

For the excelsior, the solid volume comes from the ratio of sample mass to material density

$$\frac{u_{V_s}}{V_s} = \sqrt{\left(\frac{u_m}{m}\right)^2 + \left(\frac{u_{\rho_s}}{\rho_s}\right)^2} \quad (\text{A9})$$

The uncertainty in the mass comes from the manufacturer specifications for the load cell, $u_m = 0.018 \text{ g}$, and the relative uncertainty in the density, estimated at 5 %. Given the size of sample masses, the contribution of the load cell error are essentially negligible. For the real vegetation the uncertainty in the solid volume comes from the precision of the load cell and the accuracy of readings from the graduated cylinder

$$\frac{u_{V_s}}{V_s} = \frac{1}{V_s} \sqrt{u_m^2 + u_{mL}^2} \quad (\text{A10})$$

The volume accuracy is estimated at $u_{mL} = 1 \text{ cm}^3$, so the load cell error is again a negligible component (an uncertainty of 0.018 g is equivalent to 0.018 cm^3 in volume of water).

The uncertainty in the bounding volume comes from the subtractive hull method. The dominant contribution to uncertainty here is considered to be related to the characteristic voxel size, ΔV_{vox} , as uncertainty from the macropixel resolution in the original image was very small compared to this voxel size. The volume error from voxelization is estimated based on the number of voxels on the outer surface of the object, N_{surface}

$$u_{V_b} \approx \sqrt{N_{\text{surface}}} \Delta V_{\text{vox}} \quad (\text{A11})$$

A.6 Model force

The model force predicted by Equation 3 may have small uncertainty contributions stemming from numerical errors, simplifications in boundary conditions, etc.. However, in the context of this analysis, we also consider the uncertainty in model inputs. These have measurement errors that are far more significant than pure numerical errors. These include uncertainty in the surface-to-volume ratio and the packing ratio, as described above. Each has a linear contribution to the local force. Even though the magnitude varies locally with fluid properties, the relative uncertainty in total force for a given element type (foliage, branch, or stem) can be written as

$$\frac{u_{c,F_d}}{F_d} = \sqrt{\left(\frac{u_\sigma}{\sigma}\right)^2 + \left(\frac{u_\beta}{\beta}\right)^2} \quad (\text{A12})$$

Appendix B Numerical convergence

A check on the effect of gas-phase grid resolution, independent of vegetation description, was conducted on one of the cases studied (excelsior sample EX6). Three grid resolutions were tested: . In order to keep the vegetation description consistent, the bounding volume was recomputed on the coarsest grid, and packing ratio was adjusted accordingly. In this way, the object occupied the same volume and had the same packing ratio for all gas-phase grid resolutions – it was simply intersected by more or less grid cells.

The effect of the gas-phase resolution on predicted drag is shown in Figure B1. The model can be considered converged for the baseline resolution of , as the differences with the finest resolution are negligible. Convergence is also confirmed by the fact that coarsening the baseline grid by a factor of 2 also has a minor impact. The velocity and force values are both very marginally increased, with the force following the same trend as the other resolutions.

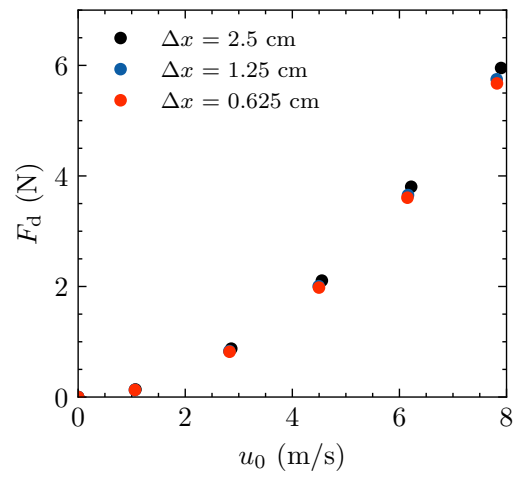


Figure B1: Evaluation of grid convergence through comparison of predicted drag of sample EX6 using three different grid resolutions.