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1 The importance of accurately representing submerged vegetation morphology in the numerical
2 prediction of complex river flow

3

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9

10 **Abstract:**

11 This paper reports a novel method for the incorporation of complex plant
12 morphologies into a computational fluid dynamics (CFD) model, allowing the
13 numerical prediction of flows around individual plants. The morphological
14 complexity, which comprises the vertical and lateral distribution of individual
15 branches and leaves is captured through terrestrial laser scanning (TLS) and is
16 maintained in the numerical prediction of flow fields. This is achieved where the
17 post-processed, voxelised plant representation is incorporated into a CFD scheme
18 through a mass flux scaling algorithm (MFSA). Flow around *Prunus laurocerasus*
19 has been modelled under foliated and defoliated states following the removal of
20 leaves. The complex plant morphologies are shown to produce spatially
21 heterogeneous downstream velocity fields, with velocity profiles that deviate
22 significantly from the idealised inflected shape. Rapid transition between the high
23 velocity free stream zone and the zone of reduced velocity in the plant wake indicate
24 shearing of flow, with the point of reattachment extending up to seven plant lengths

25 downstream. The presence of leaves significantly modifies the flow field response,
26 with development of a second, more pronounced wake structure around the dense
27 foliage. This approach provides a full flow numerical description of the pressure
28 field, enabling the vegetative drag force to be quantified. For the example given
29 here, drag force is an order of magnitude greater for the foliated state. The
30 methodology outlined here demonstrates the importance of accurately representing
31 complex plant morphology in hydraulic models, and allows drag forces and
32 coefficients to be calculated for specific plant species.

33

34 **Keywords:**

35 CFD, Channel vegetation, Terrestrial Laser Scanning, Drag coefficient

36 **Introduction:**

37 Vegetation is abundant in lowland rivers and has a profound influence on the fluvial
38 system. It affects the mean and turbulent flow field (Nepf, 2012a), provides habitat,
39 alters light availability and temperature, and regulates concentrations of oxygen,
40 carbon, and nutrients (Carpenter and Lodge, 1986). A correct understanding of the
41 influence of vegetation on flow is therefore essential and in particular its contribution
42 as an additional form of flow resistance (Kadlec, 1990). Increased flow resistance
43 produces higher water levels per unit discharge, thus increasing the risk of flooding.
44 However, a numerical description of the flow around river channel vegetation
45 canopies is challenging given the multitude of scales to be considered (Nepf, 2012b)
46 and the species-specific nature of plant morphology, which adds further complexity
47 to the quantification of vegetative flow resistance (Aberle and Järvelä, 2013; Folkard,
48 2011b; Green, 2006; Kouwen and Unny, 1973).

49 In vegetated flows, the canopy is defined as the above ground part of the plant stand
50 consisting of all branches, stems, leaves and stipes (Paul *et al.*, 2014). One
51 approach to define canopy geometry is based on the size of the individual stems and
52 blades, and the number of these elements per bed area (Nepf, 2012a). It is
53 assumed that if the canopy elements have a characteristic diameter, d , and an
54 average spacing between elements, ΔS , then the frontal area per canopy volume is
55 $A = d/\Delta S^2$. For foliated vegetation types, this is defined as the leaf area index (e.g.,
56 Kaimal and Finnigan, 1994) and when integrated over the plant height, the canopy
57 density (λf) is predicted from the frontal area per bed area, also known as the
58 roughness density (Wooding *et al.*, 1973). However, aquatic canopies exhibit a wide
59 range of morphologies and densities (Leonard and Luther, 1995; Lightbody and
60 Nepf, 2006; Valiela *et al.*, 1978), with stiffer, emergent plants tending to have

61 rounded stems and submerged grasses tending to have a blade geometry (Nepf,
62 2012a). Furthermore, variations in the size, shape and density of plant elements can
63 have a vertical dependence, which contribute towards the overall plant shape
64 (Wilson *et al.*, 2005). In natural settings, therefore, a considerable range of
65 vegetation morphologies exist.

66 This is further complicated where branches and leaves add to the total surface area,
67 therefore creating a greater obstacle to flow than the plant stem alone (Leonard and
68 Luther, 1995). Within the vegetation canopy flow is forced around each branch or
69 leaf so that the velocity field is spatially heterogeneous at the scale of these
70 elements. Vegetation structure, in particular the vertical and horizontal distribution of
71 biomass, is therefore reported to control flow through, over and around vegetation
72 layers (Tempest *et al.*, 2015). Furthermore, the velocity and driving forces within a
73 submerged canopy has a range of behaviour depending on the relative depth of
74 submergence (Nepf and Vivoni, 2000), defined as the ratio of flow depth, H , to
75 canopy height, h . In lowland river systems most submerged aquatic canopies occur
76 in the range of shallow submergence $H/h < 5$ (Chambers and Kaiff, 1985; Duarte,
77 1991), for which both turbulent stress and potential pressure gradients are important
78 in driving flow over the canopy.

79 Our current understanding of flows through shallow submerged vegetation comes
80 from physically scaled flume models, field studies, and numerical modelling studies.
81 Flume models have been used to provide a process-based understanding of
82 complex canopy flows, and the drag processes that contribute towards the
83 development of a mean velocity profile often described and approximated as S-
84 shaped, or inflected (Nepf, 2012b). The representation of the vegetation in these
85 laboratory experiments is crucial, with vegetation generally represented by: (i)

86 artificial plants or surrogates, or (ii) scaled plants or natural plants (Frostick *et al.*,
87 2011).

88 At the simplest level, discrete, rigid cylindrical elements arranged in varying spatial
89 configurations have been used to represent specific attributes such as stem density
90 in stiff, emergent plants (Liu *et al.*, 2008; Nepf, 1999). Conversely, polyethylene
91 strips have been used to represent the flexibility and reconfiguration commonly
92 observed in shallowly submerged species e.g. Mediterranean seagrass *Posidonia*
93 *oceanica* (Folkard, 2005; Folkard, 2011a). To replicate realistic structural
94 distributions of natural plants, artificial surrogates with an explicit parameterisation of
95 biomass have recently been used (Schoneboom *et al.*, 2010). Often, however,
96 artificial representations of vegetation neglect the horizontal and vertical variation in
97 plant structure observed in the natural prototype habitat, which can lead to the
98 incorrect predictions of flow at the plant and canopy scale (Tempest *et al.*, 2015).
99 Where natural vegetation is used (Järvelä, 2002; Sand-Jensen, 2003; Siniscalchi
100 and Nikora, 2012), samples can prove difficult to maintain under laboratory
101 conditions and may not capture the variety of characteristics observed in vegetation
102 (Frostick *et al.*, 2011). Misrepresentation of artificial or real vegetation morphology
103 would be translated into the flow field, and any simplification may therefore
104 compromise the representativeness of results, where alterations to the velocity and
105 pressure fields will have primary implications for the calculation of vegetative flow
106 resistance.

107 Field studies add further to our understanding, with the collection of three-
108 dimensional velocity fields around large woody debris (Daniels and Rhoads, 2003),
109 and isolated patches of in-situ submerged macrophytes (Schoelynck *et al.*, 2013).
110 Furthermore, the turbulence structure has been investigated around

111 heterogeneously distributed submerged macrophytes (Sukhodolov and
112 Sukhodolova, 2010), and tree-centred emergent bars (Sukhodolov and
113 Sukhodolova, 2014). Although these studies provide great detail of the flow field, an
114 adequate quantification of the structure of the vegetation can prove difficult.

115 In high dimensional numerical modelling, vegetation has been represented by adding
116 a drag-related bulk source and sink term into the continuity equation (Fischer-Antze
117 *et al.*, 2001; López and García, 2001). The drag force term is based on plant density
118 and an assumed rigid, cylindrical representation of vegetation, with a drag coefficient
119 of unity which is applicable for rigid cylinders with Reynolds numbers between 1×10^3
120 - 2×10^5 (Cheng, 2013; Panton, 1984). These models reproduce mean and turbulent
121 flow, although they do not effectively predict the quantitative detail of turbulence
122 namely shear and wake scales (Defina and Bixio, 2005). Such an approach has
123 been further developed by dividing the drag into stem drag and leaf drag (Yue *et al.*,
124 2007), where stem drag was modelled as above, but leaf drag was modelled
125 separately using an estimated leaf area index. An alternative approach is to include
126 individual vegetation stems. Stoesser *et al.* (2009, 2010) included an array of
127 individually represented rigid cylinders using Large Eddy Simulation, and by using a
128 fine grid ensured that drag was directly accounted for, removing the need for
129 empirical drag coefficients. Several studies have sought to incorporate flexible
130 vegetation canopies. Ikeda *et al.* (2001) developed a biomechanical plant model
131 based upon the dynamic Euler-Bernoulli cantilever beam equation within a two
132 dimensional LES framework. Marjoribanks *et al.* (2014c) developed a similar model
133 within a three-dimensional LES framework to look at arrays of semi-rigid stems
134 within flows. Similar approaches have been developed for highly flexible vegetation
135 applying a N-pendula equation (e.g. Abdelrhman, 2007; Dijkstra and Uittenbogaard,

136 2010). However, in all of these approaches each plant is represented as a single
137 stem and does not incorporate the complex plant morphology.

138 Here we report on a new methodology to incorporate a complex plant morphology
139 into a numerical model used to predict flow-vegetation interactions. We model the
140 three-dimensional velocity and pressure fields, at a high spatial resolution, around an
141 isolated laboratory plant stand. The plant is characterised by a complex morphology,
142 having a natural stem and leaf distribution. We model the flow around both a foliated
143 and defoliated representation of the plant, following manual removal of the foliage.
144 For this initial proof of concept work, a single plant stand has been selected to better
145 quantify the plant structure, and ensure any differences in the flow response can be
146 attributed to the different foliation states, therefore enabling the resistance effects of
147 the leaf body to be quantified.

148 We describe a physically-based characterisation of vegetation using terrestrial laser
149 scanning (TLS) which is subsequently incorporated into a computational fluid
150 dynamics (CFD) model by application of a mass flux scaling algorithm (Hardy *et al.*,
151 2005). Application of TLS enabled a three-dimensional model of the vegetation to be
152 rapidly captured into a Cartesian digital framework; that was subsequently
153 incorporated into numerical discretisation. For the first time, the morphological
154 complexity of the vegetation is then directly represented within the CFD model,
155 enabling a high resolution prediction of the three-dimensional velocity and pressure
156 fields, and the improved estimation of the drag force acting on the plant. The wider
157 implications for flow and sediment transport modelling around morphologically
158 complex vegetation, and future methodological developments, are discussed.

159 **Methodology:**

160 **Terrestrial Laser Scanning (TLS) and voxelisation**

161 TLS has been used to acquire a three-dimensional representation of *Prunus*
162 *laurocerasus*, an invasive species to the United Kingdom increasingly recorded in
163 riparian zones. The evergreen shrub can reach heights of 6 m, with large (0.05-0.18
164 m) oblong-acute, glossy, dark-green leaves and pale green branches (Polunin and
165 Everard, 1969; Stace, 2010). *Prunus laurocerasus* was selected for scanning given
166 its complex branch and leaf structure, and its ability to survive in laboratory
167 conditions for prolonged periods. The woody shrub shares morphological similarities
168 to woody riverine vegetation species such as *Populus nigra*, typically found on gravel
169 bars (O'Hare *et al.*, 2015). In this application, a RIEGL VZ-1000 scanner was used
170 in a controlled laboratory environment. The scanner has a beam divergence of 0.3
171 mrad, a field of view 100° x 360° and an effective measurement rate of up to 122 000
172 measurements per second. Scans were collected at a distance of 3 m, with π and θ
173 increments set to 0.012 degrees, controlling the horizontal and vertical alignment
174 respectively. Riegl (2015) report that at a distance of 10 m, the scanner has a range
175 accuracy of 8 mm, and a precision of 5 mm. The scanner recorded multiple discrete
176 returns from a single emitted pulse, improving the interrogation of vegetation
177 elements (Pirotti *et al.*, 2013), thereby heightening point density. To resolve issues
178 of occlusion, scans were acquired from four different perspectives to provide the
179 requisite overlap to capture the full three-dimensionality of the plant morphology
180 (Moorthy *et al.*, 2008).

181 Scans were completed under foliated and defoliated states, following manual
182 removal of leaves (n = 432) (See Fig. 1). Individual point clouds were registered

183 using georeferenced reflective targets in RiSCAN PRO, supplemented by multi-
184 station adjustment. Similar to the workflow of Jalonen *et al.* (2015) post-processing
185 was completed using CloudCompare software. After delineation of the area of
186 interest, erroneous data points were filtered using a statistical outlier removal tool
187 (SOR). The distance-weighted filter removed isolated points on the plant surface,
188 specifically those off-centre hits caused by the position and size of the laser pulse
189 footprint relative to the feature being scanned (Béland *et al.*, 2014). By calculating
190 the mean distance between each point in the initial point cloud and a neighbourhood
191 of its nearest points, and assuming a Gaussian distribution, those points which fall
192 outside of a defined standard deviation threshold are regarded as outliers and
193 removed (Rusu *et al.*, 2008). Following Jalonen *et al.* (2015), we calculate the mean
194 distance between every point and its 100 nearest neighbours, and remove those
195 points which fall outside of 1 standard deviation from the mean. Point clouds visually
196 match the actual plant morphology (Fig. 1a), containing $\approx 3\,500\,000$ points in the
197 foliated state (Fig. 1b), and $\approx 1\,000\,000$ points in the defoliated state (Fig. 1c). A
198 characteristic subsection of the plant, (Fig. 1b and 1c), has been incorporated into
199 the numerical model. This subsection shares the same morphological
200 characteristics (e.g. branch thickness, leaf density) as the remainder of the plant, but
201 allows flow to be solved at a higher spatial resolution in the modelling domain (see
202 below).

203 The millimetre scale spatial resolution of this point cloud exceeded what could
204 feasibly be discretised within the CFD model, owing to the computational expense
205 associated with solving flow at such high spatial resolutions. A simplification
206 procedure following the gap fraction method of Straatsma *et al.* (2008) was applied,
207 with subdivision of the scan into individual voxels (Béland *et al.*, 2011).

208 Morphological properties of vegetation have previously been established using either
209 spherical voxels (e.g., Antonarakis *et al.*, 2010) or cubic voxels (e.g., Durrieu *et al.*,
210 2008), however given the Cartesian grid structure of the CFD domain (see next
211 section), a cubic voxel representation was used. Voxelisation involved the fitting of
212 an octree structure with a user-defined maximum cell size (0.01 m) around the point
213 clouds, which captured the morphological complexity of the plant in both defoliated
214 and foliated states. The voxel size was justified given the branch diameter was in
215 the range 0.01-0.1 m, and therefore the voxel size closely approximated the finest
216 morphological elements. The voxelisation process is summarised for a subsample
217 of the defoliated and foliated scans (Fig. 1b and 1c), outputting XYZ cell centroid
218 coordinates that are read directly into the CFD discretisation (see Fig. 2).

219 ***The numerical model***

220 The numerical scheme involves a finite volume solution of the full three-dimensional
221 Navier-Stokes equations in a Cartesian coordinate system, with a Renormalized
222 Group Theory (RNG) $k-\varepsilon$ turbulence model. The closure model is applied given the
223 large degree of fluid strain associated with flow around the plant as the RNG $k-\varepsilon$
224 turbulence model calculates diffusion across the spectrum of scales (Yakhot and
225 Orszag, 1986). A hypothetical domain 350 cells long, 120 cells wide and 100 cells
226 high (4 200 000 grid cells) was created at a spatial resolution of 0.01 m. The
227 numerical simulations are run until the convergence criteria is met which is
228 dependent upon the mass conservation and momentum errors. In this application
229 the convergence criterion was set such that mass and momentum flux residuals
230 were reduced to 0.1% of the inlet flux.

231 A static representation of the plant, through the voxelised blockage, was represented
232 using the Mass Flux Scaling Algorithm (MFSA) (Hardy *et al.*, 2005; Lane *et al.*, 2002;
233 Lane *et al.*, 2004). The MFSA has previously been used to represent flow over
234 complex topography such as gravel surfaces (Hardy *et al.*, 2007), and idealised
235 single stemmed vegetation elements that are used to represent a vegetation canopy
236 (Marjoribanks *et al.*, 2014c). The MFSA represents the plant as a numerical
237 porosity, and enables the voxelised plant to occupy a specified fraction of each grid
238 cell. For each grid cell a binary occupied/unoccupied porosity is defined because the
239 0.01 m voxel size is equal to that of the 0.01 m grid cell size. The voxelised
240 blockage was incorporated 0.5 m downstream from the inlet (0.14 X/l), and centred
241 (0.5 Y/w). The bed was treated as a nonslip boundary using the logarithmic law of
242 the wall and domain side walls were considered frictionless boundaries. The
243 vegetation-flow interface is treated as an immersed boundary. Inlet conditions are
244 held constant between the defoliated and foliated model runs with the downstream
245 velocity set to 0.25 m s⁻¹ with an inlet turbulent intensity of 5%. Thus, the flow was
246 assumed to be fully turbulent and subcritical. The outlet was defined using a fixed-
247 pressure boundary condition where mass is allowed to enter and leave the domain.

248 **Results:**

249 Here we present the downstream (u -component) velocity field for the defoliated and
250 foliated cases (Fig. 2c and 2f) in plan view at 0.4 and 0.6 Z/h (Fig. 3a and 4a).
251 Under the defoliated state (Fig. 3a), individual stems introduce flow separation and
252 reattachment with the formation of narrow wakes of reduced velocity. At 0.4 Z/h ,
253 coalescence of these wakes is observed. However, this behaviour varies vertically,
254 and at 0.6 Z/h , where the branches are spaced further apart, wakes behave
255 independently. Wake coalescence would therefore depend on the separation
256 distance between individual branches. Under the foliated scenario (Fig. 4a), a
257 single, more pronounced zone of flow separation and reattachment is evident,
258 indicative of behaviour shown by a bluff object. In the foliated state, the shape of the
259 wake is vertically non-uniform, which is a function of the vertical and lateral
260 distribution of the plant morphology, and results in flow asymmetry. For example, at
261 0.4 Z/h the abundance of leaves at lower Y/w values produce an asymmetrical wake
262 structure that extends further downstream than the corresponding wake in the
263 defoliated state. For both the defoliated and foliated states similarities can be
264 observed; namely a reduction in velocity immediately upstream of the blockage, with
265 marginal flow acceleration around the blockage edges, indicative of flow in a junction
266 vortex system (Simpson, 2001). It is suggested that this canopy shear layer
267 turbulence is dominated by Kelvin-Helmholtz and Görtler-type vortices generated
268 through shear instability, which evolve with distance downstream of the plant
269 (Ghisalberti and Nepf, 2002).

270 The wake shape is further illustrated through a vertical slice down the midline (0.5
271 Y/w) (Fig. 3b and 4b). In both cases, wake shape varies considerably with Z/h . For
272 the defoliated state, development of a wake zone at 0.2-0.4 Z/h corresponds with the

273 main branching point of the plant (see Fig. 2), with a concentration of branches. The
274 wake is inclined slightly upwards, thus in the downstream direction and extends ≈ 7
275 plant lengths downstream. Marginal flow acceleration is evident around the outer
276 edge of the central branch. A more complex wake structure consisting of two
277 discrete layers is evident in the foliated state. Again, the lower wake corresponds
278 with the branching point at $0.2-0.4 Z/h$, although only extends ≈ 3 plant lengths
279 downstream. Above this, a pronounced and thicker wake zone at $0.45-0.65 Z/h$
280 corresponds with the dense foliation, and extends ≈ 7 plant lengths downstream. The
281 dense foliation component is influential in producing a localised velocity response.

282 The morphological complexity of the plant introduces additional flow heterogeneity,
283 therefore velocity profiles begin to deviate from the idealised inflected profiles that
284 are associated with canopy flows (Fig. 5a, inset graph). Fig. 5 provides evidence for
285 three distinct velocity zones in the vertical, namely: a zone of relative flow
286 acceleration beneath the bulk of the plant in the near bed region (sub-canopy flow), a
287 zone of flow acceleration above the plant in the free stream zone, and between
288 these a non-uniform low velocity zone associated with flow deceleration around the
289 plant blockage. The shape of the vertical velocity profiles clearly differ between the
290 defoliated and foliated states. When defoliated, the velocity minima is positioned
291 lower in the flow depth, and associated with the point at which the main branch splits
292 into sub-branches (see Fig. 2). When foliated, however, the velocity minima is
293 shifted higher in the flow, and associated with the main leaf body. The magnitude
294 and size of the low velocity zone in the foliated state is exaggerated relative to the
295 defoliated state, illustrating the important role of the leaf body in modifying the flow
296 disturbance. In both foliation states the accelerated sub-canopy flow component
297 appears to be similarly sized and shaped, indicating that distance between the bed

298 and base of the main plant blockage influences the characteristics of this zone. The
299 velocity profiles show that with increasing distance downstream, the flow begins to
300 recover, with velocity profiles becoming more modulated, and velocities reverting
301 towards the inlet velocity of 0.25 m s^{-1} .

302 Especially in the foliated state proximal to the blockage (Fig. 5a and Fig. 5b), a sharp
303 transition is evident between the reduced velocity zone and free stream zone,
304 characterised by flow acceleration, with this velocity discontinuity indicative of shear
305 layer formation and the presence of Kelvin-Helmholtz instabilities (Ghisalberti and
306 Nepf, 2002). The shear layer appears more prominent where the plant thickness is
307 larger and therefore the shear layer scales with the local plant thickness. Vortex
308 growth stops when turbulent energy production is equal to dissipation (Ghisalberti
309 and Nepf, 2004).

310 At the wake scale, mean kinetic energy is converted into wake-generated turbulent
311 kinetic energy at the scale of the plant stems (Ghisalberti and Nepf, 2002) and
312 therefore analysis of the turbulent kinetic energy (TKE) provides an estimation of the
313 amount of form drag introduced by the plant (Raupach and Shaw, 1982). Direct
314 comparisons between the defoliated and foliated states are shown at $0.45 Z/h$ (Fig.
315 6a and 6b). In both cases, zones of high TKE ($> 0.04 \text{ m}^2/\text{s}^2$) are observed proximal
316 to the outer edge of the plant, driven by the forcing of flow around the blockage,
317 resulting in flow acceleration (u -component) and lateral movement (v -component).
318 For the defoliated state, these high TKE zones are enclosed around individual
319 branches, whereas in the foliated state the zones are comparably larger and extend
320 a greater distance from the vegetation front, due to a longer, more pronounced
321 disturbance to the v -component of velocity. Because of the complex, interacting

322 nature of the wakes in the defoliated state, the leeward zone of low TKE (< 0.015
323 m^2/s^2) is more fragmented and extends a greater distance downstream than in the
324 foliated state. Again this demonstrates canopy shear layer instability, dominated by
325 Kelvin-Helmholtz and Görtler-type vortices evolving with distance downstream of the
326 plant.

327 Pressure fields are analysed to calculate the drag force and subsequent drag
328 coefficients acting on the plant (Marjoribanks, 2013). Fig. 7a and 7b show the
329 pressure fields at $0.45 Z/h$. When defoliated, the high pressure zone located directly
330 upstream of the blockage is isolated about individual branches. When foliated,
331 however, this zone has coalesced to form a comparatively larger, single body
332 characterised by higher pressures. Similarly, downstream of the plant, isolated
333 zones of low pressure are associated with individual branches when defoliated,
334 compared with a much more pronounced and extended low pressure zone when
335 foliated.

336 **Calculation of drag forces**

337 The drag force is calculated by integrating the difference in the pressure field acting
338 normal to the vegetation surface over the entire lateral extent of the plant. We sum
339 the difference in pressure from immediately upstream and downstream of the plant.
340 This is achieved by applying a mask to the three-dimensional vegetation extent, and
341 extracting pressure values from one cell upstream and one cell downstream of the
342 mask:

$$F_d = \int_A (p_f - p_b) dA \quad (1)$$

343 where F_d is the drag force (N/m^2), p_f is the pressure at the blockage front (Pa), p_b is
344 the pressure at the blockage back (Pa), and A is the frontal area (m^2). In this
345 instance where the plant is represented by a 0.01 m voxel size, this gives a cell area
346 of 0.0001 m^2 . To calculate the plant frontal area, we count the number of cells at the
347 blockage front, and multiply this by the cell area. A full discussion of the drag
348 calculation is provided by Marjoribanks *et al.* (2014b). Drag forces of 0.15 N/m^2 and
349 1.74 N/m^2 are calculated for the defoliated and foliated states respectively. This
350 order of magnitude difference is attributed to the influence of the additional
351 morphological complexity introduced by leaf elements, which result in a different flow
352 response as drag increases with foliage density (Wilson *et al.*, 2003). As previously
353 observed, leaves are shown to introduce a second wake structure that extends ≈ 7
354 plant lengths downstream, resulting in a more spatially heterogeneous velocity field.
355 This corresponds with the more pronounced TKE patterns observed in the foliated
356 case, indicating a greater form drag contribution. Both of these factors result from
357 the greater number of blocked cells in the foliated state, imparting a greater

358 disturbance on the flow. The drag force values are of a similar order of magnitude to
359 the direct measurements of vegetative drag force ($\approx 0-10 \text{ N/m}^2$), for small natural
360 woody trees, undertaken by Jalonen and Järvelä (2014).

361 Drag forces are used to calculate a drag coefficient, following:

$$C_d = \frac{F_d}{\frac{1}{2}\rho u^2 A} \quad (2)$$

362 where C_d is the drag coefficient, ρ is the density (kg/m^3), and u is the inlet velocity (m
363 s^{-1}). Drag coefficients are well understood for simple geometric shapes (e.g.
364 cylinders), but are less well understood for the complex geometries associated with
365 natural vegetation (Marjoribanks *et al.*, 2014a). Modelling studies typically assign a
366 drag coefficient value of unity for vegetation, however this is only applicable to the
367 simplest reed and grass type plants. A value of unity is true for a single cylinder with
368 Reynolds numbers between $1 \times 10^3 - 2 \times 10^5$, although deviates significantly for more
369 complex vegetation as it is a function of both vegetation density and stem Reynolds
370 number (Tanino and Nepf, 2008). For sparsely configured leafy shrub communities,
371 the flume experiments of Hui *et al.* (2010) report drag coefficients of up to 4. Here,
372 we calculate drag coefficients of 1.54 and 1.24 for the defoliated and foliated states
373 respectively, exceeding the typically assumed value of 1. An inverse trend between
374 drag force and drag coefficient is surprising given the drag coefficient in the
375 defoliated case is higher, when the drag force is an order of magnitude lower than
376 the foliated case. This discrepancy can be explained by morphological differences.
377 Namely, the dominance of individual branches in the defoliated state, compared to
378 the dominance of a single leaf body of the foliated state, where sheltering effects
379 reduce the imposed resistance on the downstream end of the plant.

380 **Discussion and potential applications:**

381 Analysis of downstream velocity, turbulent kinetic energy and pressure field
382 simulations have demonstrated the importance of explicitly representing the
383 morphological complexity of plants in the numerical description of flow in vegetated
384 channels. The vertical and lateral distribution of the plant morphology is shown to
385 form canopy shear layer turbulence, likely to be dominated by Kelvin-Helmholtz and
386 Görtler-type vortices, which evolve downstream of the plant (Ghisalberti and Nepf,
387 2002). The approach provides a high resolution, spatially distributed set of modelled
388 hydraulic data which can provide the framework for evaluating turbulence-
389 vegetation-energy loss relationships, and in particular a means for calculating drag
390 coefficients for individual plant species.

391 The ability to incorporate morphologically complex vegetation into a numerical
392 scheme has major implications for the modelling of flow, sediment transport and the
393 associated evolution of vegetated and partially-vegetated near surface landscapes.
394 When modelling flow, the approach better allows us to understand the flow
395 disturbance introduced by vegetation, providing a full flow field simulation of the
396 three-dimensional velocity and pressure fields. This extends beyond the work of
397 Manners *et al.* (2013), who used a vertically averaged two-dimensional model
398 around stands of *Tamarix spp.* We show that the vertical and lateral position of the
399 vegetation, specifically the distribution of the main body of the foliage, results in a
400 complex velocity field, and this directly influences the shape of the vertical velocity
401 profile. Therefore across different species, it is likely that the distribution of foliage
402 will be significant in controlling the flow patterns observed. For shrubs with an open
403 area beneath the primary leaf mass, Freeman *et al.* (2000) demonstrated that flow is
404 significantly diverted beneath the canopy, with an acceleration of the sub-canopy

405 flow. Similar velocity profiles were noted in field studies of flow around natural
406 willows by Bölscher *et al.* (2005). In this paper we have successfully modelled
407 similar velocity profiles (Figure 5), and this sub-canopy flow component will have
408 direct implications for elevated bed shear stresses around the plant and for surface
409 scour. When modelling flow around woody vegetation types, consisting of both a
410 branch and foliage component, there is a clear need to accurately represent this
411 morphological complexity. An over-simplified representation (e.g. a simple cylinder)
412 would fail to capture the full complexity of flow field, omitting key features such as the
413 sub-canopy flow, as well as the structure of wake shape. Järvelä *et al.* (2006)
414 specify that for predicting erosion and sediment transport, a three-dimensional
415 modelling solution that can adequately model the turbulent flow field is needed. Our
416 approach meets these demands, and therefore has potential for modelling sediment
417 transport dynamics. Crucially, we are developing the method to include a digital
418 elevation representation of the bed, which is coupled to a sediment routing model,
419 thereby offering the ability to model vegetation-flow-sediment interactions
420 simultaneously. This development will allow sediment particles to be tracked around
421 vegetation, and the patterns of local scour and deposition to be mapped.

422 However, the results presented here describe only a static representation of a single
423 plant morphology. Aquatic vegetation is seldom found in isolation (Sand-Jensen and
424 Madsen, 1992), and as such the forces on individual plants can be reduced due to
425 sheltering and through the reduced velocities in wakes from upstream plants.
426 Furthermore, flow forcing will cause foliage reconfiguration through streamlining,
427 which will subsequently reduce the drag. This has been shown to be more important
428 in drag reduction than stem bending and enables plant survival through either static
429 or dynamic reconfiguration (Nikora, 2010; Usherwood *et al.*, 1997). These

430 reconfiguration processes occur over a range of spatial scales from individual leaves
431 to entire plant-patches (Albayrak *et al.*, 2013; Sand-Jensen, 2003), and therefore an
432 explicit representation of changes to plant posture through time is also essential.
433 Work is therefore currently underway to develop a dynamic approach that accounts
434 for multiple dynamic, morphologically complex plants, incorporating reconfiguration
435 and subsequent form drag reduction by developing further the approach of
436 Marjoribanks *et al.* (2014c). This involves applying a time-varying biomechanical
437 model coupled with Large Eddy Simulation (LES) to predict plant motion through
438 time.

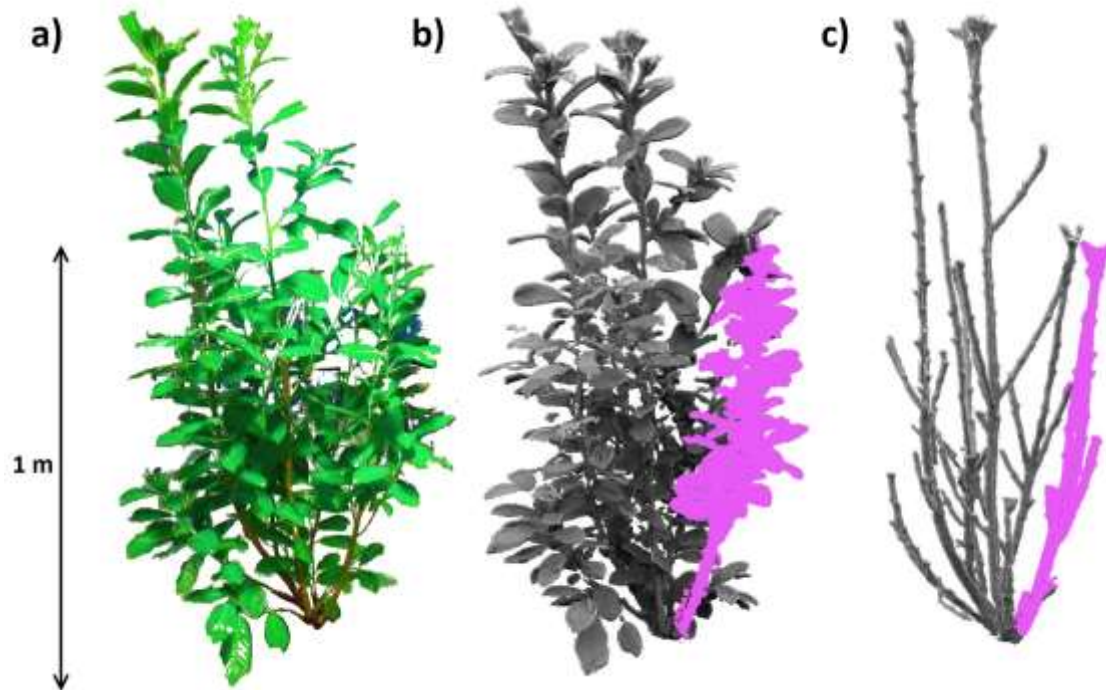
439 Recent experimental work has shown how the interaction of neighbouring emergent
440 vegetation patches can influence deposition dynamics (Meire *et al.*, 2014). This has
441 been extended into a numerical scheme, where de Lima *et al.* (2015) used CFD to
442 show that patch distributions and interactions may be responsible for the feedbacks
443 that influence the evolution of vegetated landscapes at the channel scale. However,
444 in both examples vegetation is represented by cylinders of varying densities.
445 Developing an approach which includes multiple, dynamic representations of
446 morphologically complex plants derived from TLS will allow sediment dynamics to be
447 further explored. Furthermore, the approach we propose is not limited to woody
448 species associated with riverine settings, it is possible to apply the methodology to a
449 vegetated estuarine environment where sediment dynamics are of critical
450 importance.

451

452 ***Acknowledgements:***

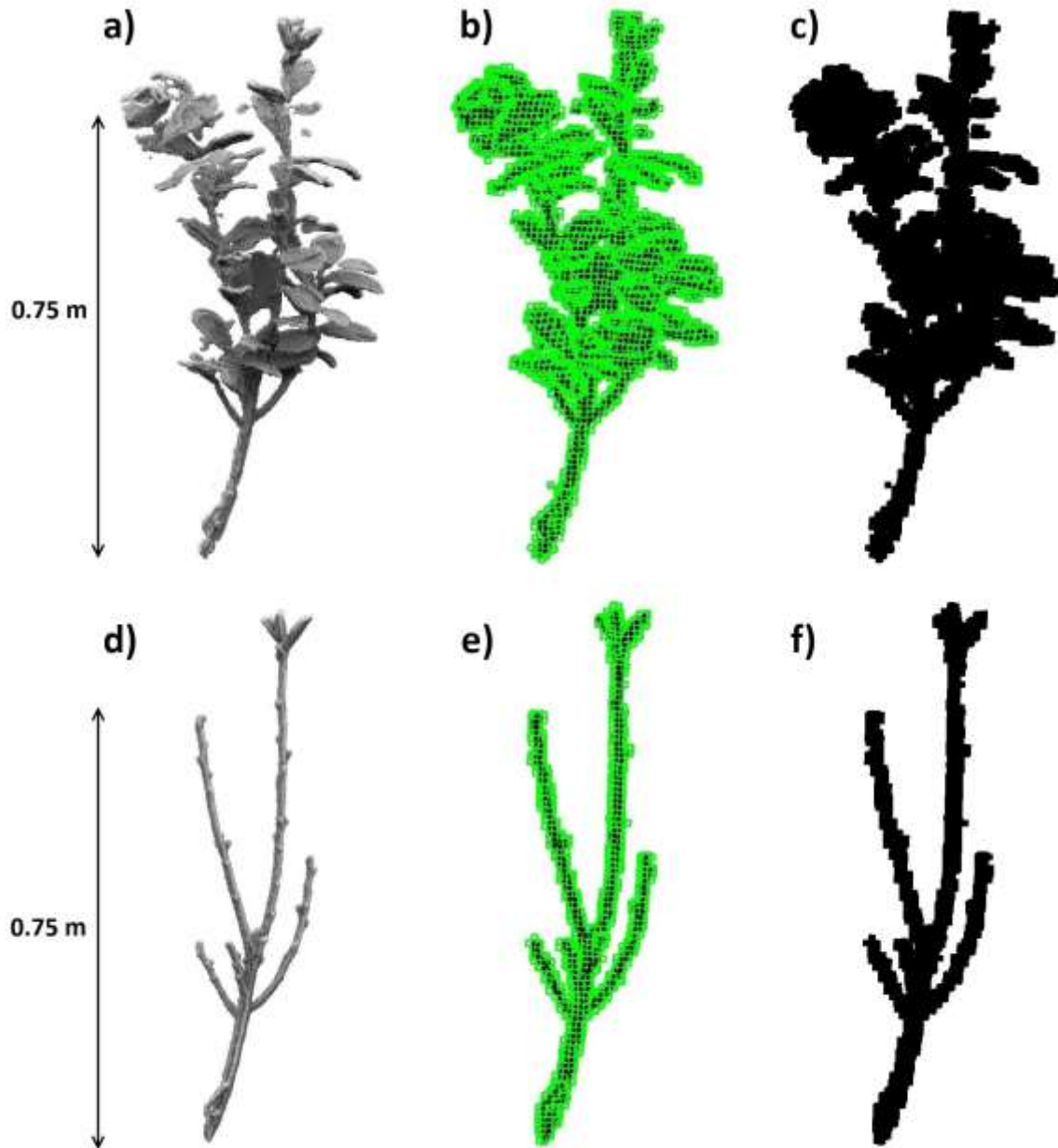
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454 used in this manuscript can be obtained by contacting the lead author. We are
455 grateful to the Editor and two anonymous referees for providing helpful comments
456 that have led to significant improvements in this manuscript.

457



459

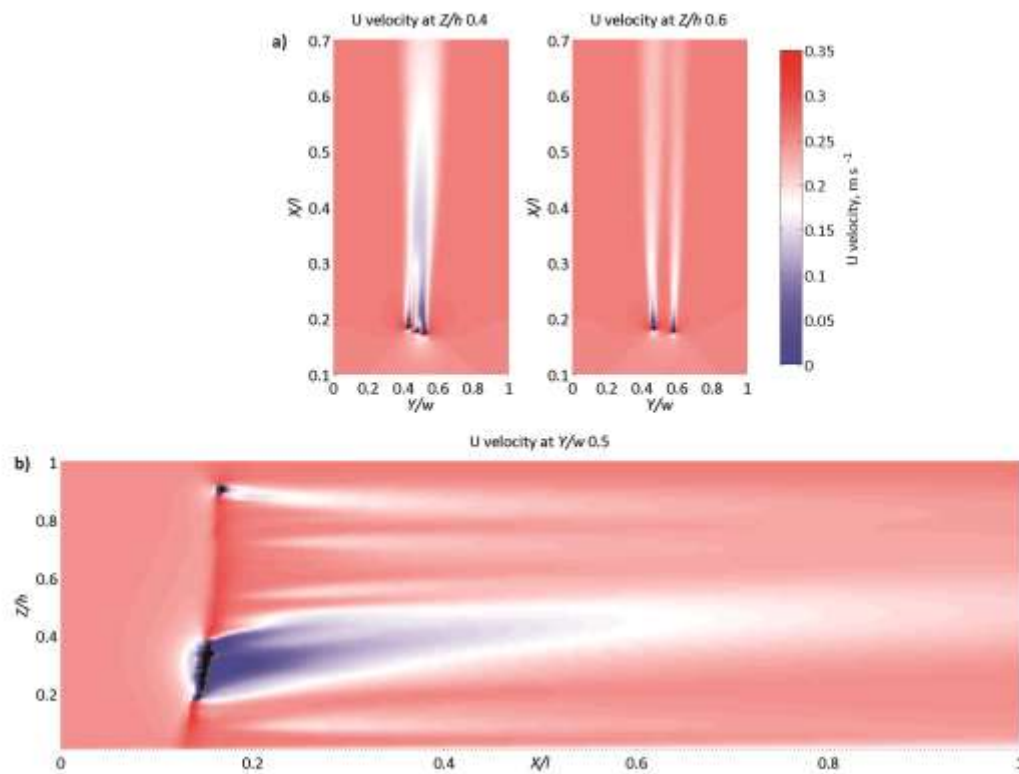
460 **Figure 1:** Three-dimensional point cloud of *Prunus laurocerasus* captured using
461 *TLS*: (a) photograph in foliated state, (b) post-processed foliated point cloud with
462 subsection used in numerical model highlighted (Fig. 2), (c) post-processed
463 defoliated point cloud, following manual removal of leaves ($n = 432$), with
464 characteristic subsection highlighted (Fig. 2).



465

466 **Figure 2:** Stages of the voxelisation process, for the foliated (a-c) and defoliated (d-f)
 467 subsections: (a and d) illustrate the post-processed point cloud; (b and e) the user-
 468 defined octree structure with a cell size of 0.01 m fitted around the point cloud; and
 469 (c and f) the voxelised representation, following extraction of *XYZ* coordinates of
 470 octree centroids.

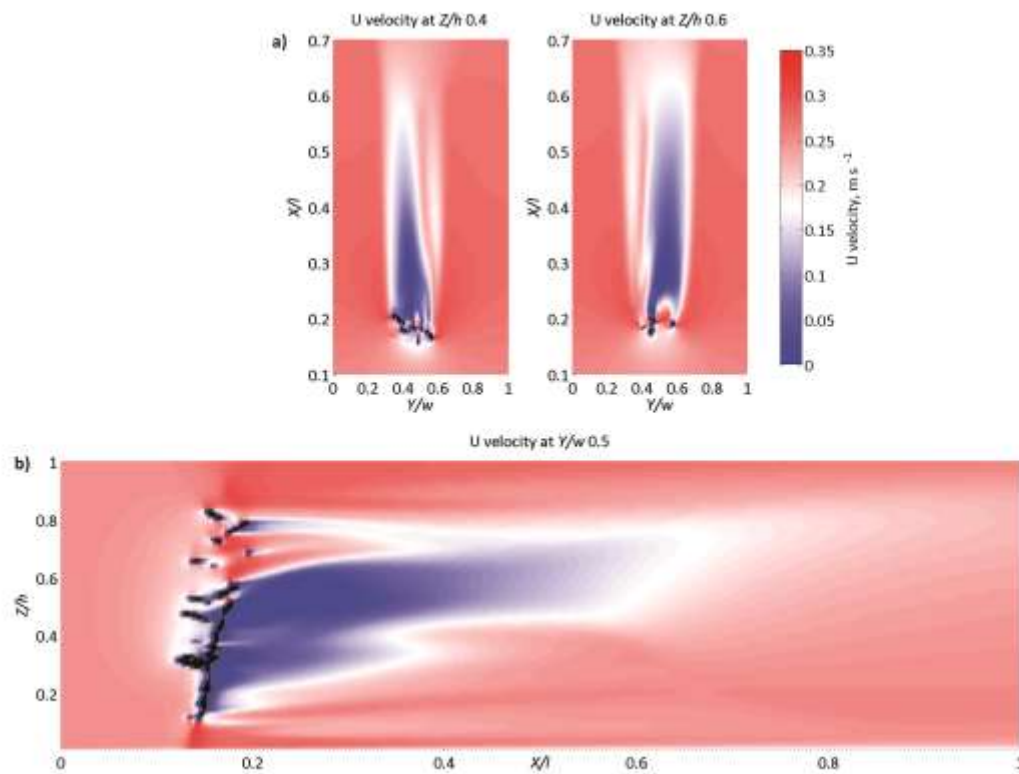
471



472

473 **Figure 3:** Downstream (u -) velocity field data for the defoliated state: (a) slices at 0.4
 474 and 0.6 Z/h . The position of the plant is marked as the solid black region.
 475 Downstream wakes can coalesce or act independently from one another, based on
 476 the separation distance of individual branches. (b) Vertical slice taken at the midline
 477 (0.5 Y/w), where a spatially non-uniform wake shape in the vertical dimension is
 478 shown. The wake zone at 0.2-0.4 Z/h is associated with the main branching point,
 479 and extends ≈ 7 plant lengths downstream.

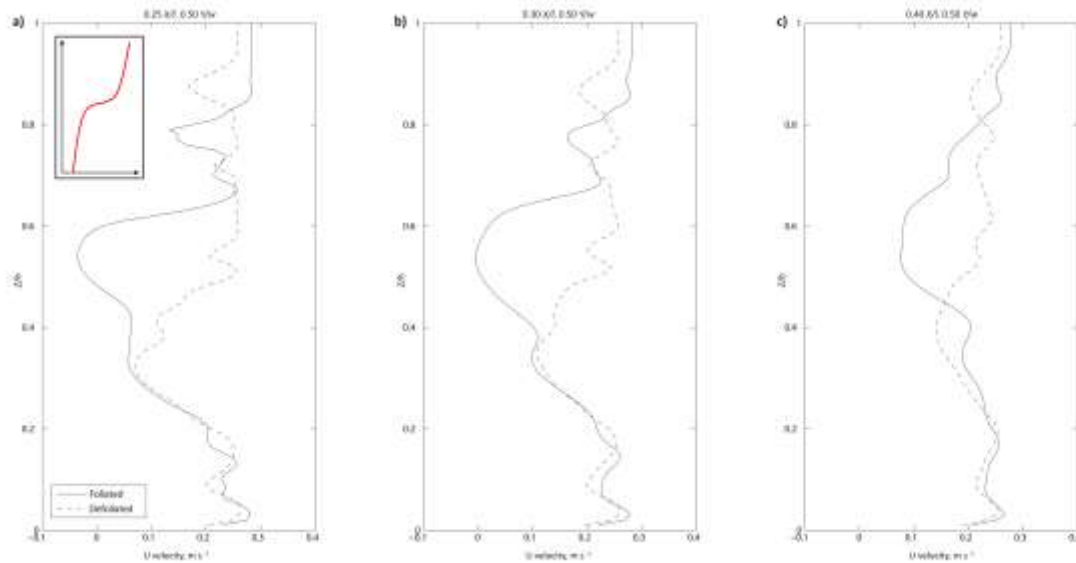
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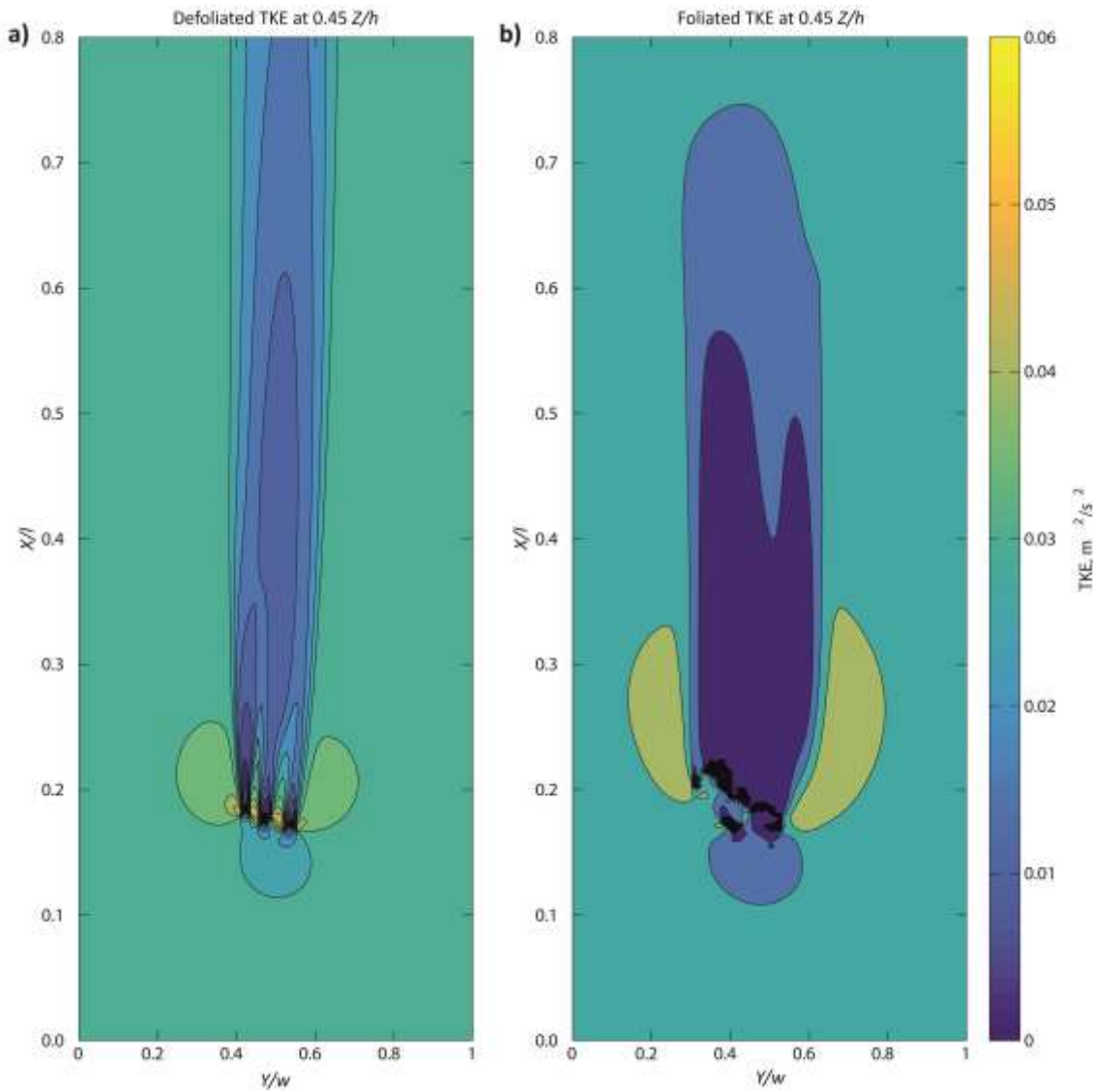
482 **Figure 4:** Downstream (u -) velocity field data for the foliated state: (a) slices at 0.4
 483 and 0.6 Z/h show a single, more pronounced zone of flow separation and
 484 reattachment, indicative of behaviour shown by a bluff object. (b) Vertical slice taken
 485 at the midline (0.5 Y/w) illustrates two discrete wakes. Similarly to the defoliated
 486 case, the lower wake corresponds with the branching point at 0.2-0.4 Z/h although
 487 only extends ≈ 3 plant lengths downstream. Above this, a more pronounced wake at
 488 0.45-0.65 Z/h corresponds with the bulk of the leafy blockage, extending ≈ 7 plant
 489 lengths downstream. The leafy component has a first order control on the
 490 production of a spatially heterogeneous velocity field.

491



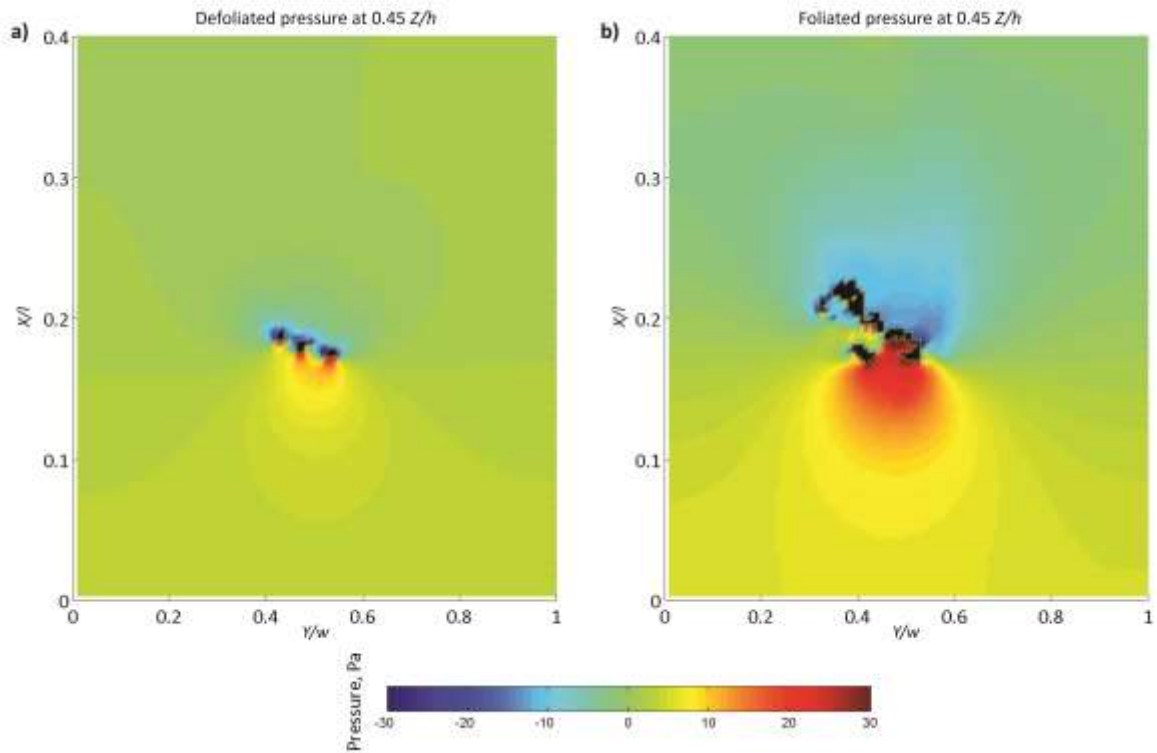
492

493 **Figure 5:** Vertical velocity profiles extracted from the midline ($0.5 Y/w$) at increasing
 494 distances downstream: (a) $0.25 X/l$, (b) $0.30 X/l$, (c) $0.40 X/l$. The inset graph in (a)
 495 illustrates an idealised inflected velocity profile often used to characterise vegetated
 496 flows. The velocity profiles illustrate the complex vertical structure in the wake of the
 497 flow. Three velocity zones are identified, namely: a zone of relative flow acceleration
 498 beneath the bulk of the plant in the near bed region (sub-canopy flow), a zone of flow
 499 acceleration above the plant in the free stream zone, and between these, a non-
 500 uniform low velocity zone associated with flow deceleration due to the bulk of the
 501 plant blockage. The magnitude and size of the low velocity zone is exaggerated in
 502 the foliated state, where the leaf body acts to further decelerate flow in the wake.



503

504 **Figure 6:** Turbulent Kinetic Energy (TKE) for (a) defoliated and (b) foliated
 505 scenarios, $0.45 Z/h$. In both cases, a zone of high TKE ($> 0.04 \text{ m}^2/\text{s}^2$) is evident
 506 proximal to the outer edge of the vegetation. In the defoliated scenario, this is
 507 enclosed by a slightly lower zone of TKE ($0.03\text{-}0.04 \text{ m}^2/\text{s}^2$), whereas in the foliated
 508 scenario, the high TKE zone is larger, and persists in the downstream direction.
 509 Overall, TKE patterns indicate a greater form drag contribution in the foliated case.



510

511 **Figure 7:** Pressure fields at $0.45 Z/h$ for: (a) the defoliated state, where individual
 512 branches cause the formation of isolated zones of high pressure upstream, and low
 513 pressure downstream. (b) The foliated state exhibits different behaviour, with the
 514 formation of a more pronounced zone of high pressure upstream, and coalescence
 515 of the low pressure zone downstream; again indicative of bluff behaviour.

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