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### Citation for published version:

Bau', V & Perona, P 2020, 'Biomechanical properties and resistance to uprooting of laboratoryscale wood logs', *Journal of Geophysical Research: Biogeosciences*. <https://doi.org/10.1029/2020JG005782>

### Digital Object Identifier (DOI):

[10.1029/2020JG005782](https://doi.org/10.1029/2020JG005782)

### Link:

[Link to publication record in Edinburgh Research Explorer](#)

### Document Version:

Peer reviewed version

### Published In:

Journal of Geophysical Research: Biogeosciences

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1           **Biomechanical properties and resistance to uprooting of**  
2                           **laboratory-scale wood logs**

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5           **Key Points:**

- 6           • Wood log growth experiments reveal uniform distribution of root biomass along the  
7           trunk
- 8           • Uprooting tests show linear and nonlinear dependencies of mechanical anchoring on  
9           root biomass
- 10          • Survival to uprooting by flow of young rejuvenated wood logs occurs within win-  
11          dows of opportunity

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## Abstract

Wood dynamics affects riparian ecosystem functioning and river morphology. The spatial and temporal dynamics of wood pieces in river corridors, in particular of deposited rejuvenated wood logs, depend on their biomechanical properties and resistance to uprooting. The ability of stranded wood logs to withstand drag forces depends on how efficiently their roots have sprouted and on the interarrival time, magnitude, and duration of the moderate floods to which they are subjected. We performed static pullout tests on small-scale wood logs (*Salix* species) of 4 different sizes, growth stages, and sediment moisture content. Statistics of root biomass growth rate and related spatial distribution along the trunk reveal important insights for upscaling dynamics. Similarly, force-displacement curves indicate the maximum resistance and related energy for uprooting. Autocorrelation analysis of the sequence of force drops in the force-displacement signal reveals the statistical nature of the mechanism of load redistribution among roots. These results are then used to advance a physically-based mathematical model of the resistance of wood log roots to flow-induced drag forces. Given that the magnitude, duration, and return period of hydrologic events are typically correlated, our model implies the existence of windows of opportunity for wood logs to either survive or re-mobilize.

## 1 Introduction

Riparian zones are defined as complex transitional ecotones occurring between terrestrial and river ecosystems [Gregory *et al.*, 1991; Malanson, 1993; Gurnell *et al.*, 1995; Tabacchi *et al.*, 1998; Naiman *et al.*, 2005]. Within riparian zones, the hydrological, geomorphic, and ecological processes interact over wide spatial and temporal scales and contribute to bidirectional exchanges of energy and material [Likens and Bormann, 1974; Johnston and Naiman, 1987; Bendix and Hupp, 2000; Hungr *et al.*, 2001; Steiger *et al.*, 2005; Wilford *et al.*, 2005; Pinay *et al.*, 2018]. A key material exchange between rivers and adjacent riparian areas involves the transfer of wood logs to stream channels [Latterell *et al.*, 2006; Naiman *et al.*, 2000; Gurnell *et al.*, 2005; Wohl, 2019], a process that often takes place after high magnitude flooding events [Mao *et al.*, 2013; Comiti *et al.*, 2016; Ruiz-Villanueva *et al.*, 2016; Zischg *et al.*, 2018]. The presence of wood material has been recognised to be as fundamental a component of woodland fluvial ecosystems as sediment and riparian vegetation [Anderson *et al.*, 1978; Abbe and Montgomery, 1996; Gurnell *et al.*, 2002; Gregory *et al.*, 2003; Tockner *et al.*, 2003; Seo and Nakamura, 2009; Beckman and

44 Wohl, 2014; Wohl and Scott, 2017]. Wood accumulations may have an impact on flow re-  
45 sistance, affecting the pattern and geomorphology of rivers [Young, 1991], and local sedi-  
46 mentation and erosion processes [Gippel *et al.*, 1996; Grunell, 1997; Brooks and Brierley,  
47 2002]. Besides providing a niche for aquatic and terrestrial lifeforms [Fisher and Likens,  
48 1972], wood accumulations may also hinder the downslope transfer of both organic mate-  
49 rials and nutrients and promote their retention [Thompson, 1995]. As a result, wood logs  
50 may act as ecosystem and geomorphological engineers by initiating island nuclei, sustain-  
51 ing water quality, providing nutrients and shelter for organisms, and creating a variety of  
52 physical habitats [Décamps and Naiman, 1990; Naiman and Decamps, 1997; Francis *et al.*,  
53 2008; Corenblit *et al.*, 2011; Welber *et al.*, 2012; Gurnell *et al.*, 2001].

54 The motion of wood logs in rivers involves three steps: recruitment, transport, and  
55 deposition [Gasser *et al.*, 2019]. Recruitment is a combination of selection and deliv-  
56 ery mechanisms of wood logs from river bedforms and banks into streams, and is trig-  
57 gered by stochastic geophysical events such as hillslope failure [Keller and Swanson, 1979;  
58 Nakamura and Swanson, 1993; Comiti *et al.*, 2016; Cadol *et al.*, 2009; Rigon *et al.*, 2012;  
59 Iroumé *et al.*, 2015], bank erosion [Sedell and Froggatt, 1984; Gurnell *et al.*, 2000; Downs  
60 and Simon, 2001; Moulin and Piégay, 2004; Lassette *et al.*, 2008; Ulloa *et al.*, 2015],  
61 snow avalanches [Bebi *et al.*, 2009], and stand-replacing events (e.g. tree windthrow [Welty  
62 *et al.*, 2002] and wild fires [Benda *et al.*, 2003; Rosso *et al.*, 2007]). Transport refers to  
63 the mobilization of wood logs in river corridors. This is also influenced by river morphol-  
64 ogy, first-order control on the wood regime [Wohl, 2019], and wood properties (e.g., ori-  
65 entation, size, and density) [Gurnell *et al.*, 2002; Braudrick and Grant, 2000; Wohl, 2011;  
66 Ruiz-Villanueva *et al.*, 2016]. Finally, deposition is the process by which wood logs set-  
67 tle on floodplains and alluvial bedforms, such as bars and islands, as a result of low flow  
68 conditions or narrowing of the river section [Gasser *et al.*, 2019]. Deposition of wood in  
69 rivers has been widely observed and its important ecological functions studied in detail,  
70 including maintenance of aquatic and terrestrial habitats and provision of food resource  
71 for aquatic organisms [Gregory *et al.*, 2003; Gurnell and Petts, 2006]. The deposition of  
72 wood pieces on river bedforms, and their interactions with river processes are believed  
73 to play an important role in the geomorphic complexity and ecological diversity of rivers  
74 [Montgomery *et al.*, 2003; Gurnell *et al.*, 2005; Francis, 2007; Gurnell *et al.*, 2012; Ruiz-  
75 Villanueva *et al.*, 2016]. Notably, this is also influenced by the ability of many riparian  
76 wood species to re-sprout and develop adventitious roots once deposited, thus leading to

77 the emergence of pioneer landforms [Gurnell *et al.*, 2005]. For example, river bars in the  
78 Tagliamento river were found to be significantly affected by the regeneration of driftwood  
79 [Gurnell and Petts, 2002; Francis and Gurnell, 2006]. Species that can resprout and re-  
80 grow invariably reproduce vegetatively. For instance, in a study of the riparian forests of  
81 the Pacific Coastal Ecoregion, Naiman *et al.* [2000] report that redwood, willow, poplar,  
82 and ash are notable examples of species likely to develop roots from disseminated frag-  
83 ments. Karrenberg *et al.* [2002] also observed that *Salicaceae* species can re-sprout vigor-  
84 ously from deposited vegetative fragments. Figure 1 shows three examples of wood frag-  
85 ments resprouting and rooting again, after deposition on moist sediment.

86 Meanwhile, the successful sprouting and establishment of roots from rejuvenated  
87 wood-logs on river bedforms depends on the resistance of roots to remobilization or up-  
88 rooting by flow, which is determined by the biomechanical properties of the root-soil ar-  
89 chitecture [Edmaier *et al.*, 2011]. Edmaier *et al.* [2011] found that the mechanism of plant  
90 uprooting by flow can occur almost instantaneously (uprooting of Type I) when plants are  
91 in their early stage of growth or as a time delayed process (uprooting of Type II) when  
92 flow-induced drag and bed erosion processes exceed the anchoring resistance exerted by  
93 the root system, as confirmed by Bywater-Reyes *et al.* [2015] in a field setting. Substan-  
94 tial research has been devoted to understanding the dynamics of recruitment and transport  
95 [Braudrick *et al.*, 1997; Bocchiola *et al.*, 2002; Daniels, 2006; MacVicar and Piégay, 2012;  
96 Iroumé *et al.*, 2015; Ravazzolo *et al.*, 2015; Ruiz Villanueva *et al.*, 2014; Martin and Benda,  
97 2001], but has not yet explored the biomechanical properties and root resistance of de-  
98 posited regenerating wood logs. From this perspective, the biological timescale becomes  
99 fundamentally important because the mechanism of remobilization of wood logs results  
100 from competition dynamics between the plant biological growth rate and the frequency  
101 and magnitude of flood disturbance. Therefore, knowledge of the biomass developed by  
102 resprouted wood logs at different timescales and quantification of the respective rooting  
103 anchoring resistance would facilitate assessment of the roots' ability to withstand water  
104 drag forces. However, assessment of the biomechanical properties of wood logs in situ is  
105 not an easy task, owing to several constraints that make wood deposition and remobiliza-  
106 tion processes difficult to monitor. For instance, depending on the obstacle-to-sediment  
107 size ratio, scour and deposition processes may have a significant influence on remobiliza-  
108 tion of wood logs. However, tracking river processes in field-scale experiments is difficult

109 to achieve. Therefore, it is necessary to investigate the resilience of wood logs by under-  
110 taking controlled laboratory experiments.

111 The aim of this paper is to study the growth dynamics of small-scale wood logs and  
112 explore their mechanical resistance through pullout experiments. Vertical uprooting experi-  
113 ments that measure root pulling-out resistance provide the most efficient way to determine  
114 the root anchorage of a plant [Ennos and Pellerin, 2000]. Rooting resistance is typically  
115 quantified by means of force/extension curves related to parameters that express root archi-  
116 tecture (such as root length and root diameter) [Edmaier, 2014; Bywater-Reyes et al., 2015;  
117 Bankhead et al., 2017; Karrenberg et al., 2003]. This approach provides insights into the  
118 complex dynamics of deposition and remobilization of wood logs in rivers.

119 In this work, 326 plant uprooting tests involving logs of different sizes were suc-  
120 cessfully performed for two different sediment moisture contents and at different growth  
121 stages. The prototype plant comprised wood cuttings (*Salix* species), which served as a  
122 surrogate for small wood logs. Cuttings of four different sizes were tested in order to ad-  
123 vance upscaling rules that will enable the biomechanical properties of *Salix* wood logs to  
124 be reproduced correctly at field scale. Architectural parameters, including below-ground  
125 biomass (e.g., root length) and above-ground biomass (e.g., branch size) were computed in  
126 order to estimate the flow-induced drag force on a wood log when subjected to the stream  
127 velocity during a certain flooding event. This enabled us to back-calculate the magnitude  
128 and the return time of hydrologic events that may remove rejuvenated logs at early stages  
129 of growth, depending on the relative elevation of sites where logs are deposited. The un-  
130 derstanding gained from the present results will help improve deterministic and stochastic  
131 models for riverbed vegetation dynamics (e.g. encroachment, deposition, persistence, re-  
132 mobilization) and to inform river restoration and management projects.

## 138 **2 Material and methods**

### 139 **2.1 Material and experimental setup**

140 The cuttings used in the present experiments were harvested from a single *Salix*  
141 *fragilis* located on the riverbanks of the Braid Burn, close to the King's Building cam-  
142 pus in Edinburgh. This species is a member of the *Salicaceae* family, which have a high  
143 capacity to sprout roots when fragments are exposed to adequate moisture conditions (e.g.  
144 Tyce [1957]) and reproduce freely from cuttings or broken branches [Howell et al., 1994].



133 **Figure 1.** Examples of regrowth stages of wood logs of different sizes that have sprouted on river bars:  
 134 a) sprouting of a willow branch from a log deposited on a bar in the Sense River, Switzerland (photograph  
 135 courtesy of V. Ruiz-Villanueva); b) deposited wood fragments on a bar in the Thur River, Switzerland (photo-  
 136 graph: P. Perona) where it can be deduced from the stage of evolution of the branches that the root system of  
 137 the logs may have developed a certain anchoring resistance; and c) example of sprouting from below ground.

145 Furthermore, the use of cuttings rather than seedlings allowed processes that occur widely  
 146 in nature to be simulated, given that wood fragments deposited on river bedforms mainly  
 147 derive from broken branches or trunks of trees transported during floods. In addition,  
 148 the cuttings reproduce, at small scale, a tree trunk or wood log and facilitate the design  
 149 of an upscaling procedure. Each cutting was assigned randomly to rhizoboxes and was  
 150 planted horizontally, half-embedded in washed mineral sand with a mean grain size of  $\sim 1$   
 151 mm. This sediment size class is often found on river bars and islands (e.g. see *Moggridge*  
 152 [2007]; *Pasquale et al.* [2011]). However, it should be noted that use of sand on its own  
 153 may not be fully representative of the variability of the sediment calibre encountered on  
 154 the surface (and subsurface) of sediment patches. Even so, sand can be useful as an ide-  
 155 alised prototype soil medium in which to test plant uprooting resistance at laboratory scale  
 156 (e.g. see *Edmaier* [2014]; *Calvani et al.* [2019]). The sediment depth was set equal to 16  
 157 cm in order to avoid root growth being constrained by the bottom of the box. Rhizoboxes  
 158 are permeable to water and so were placed inside a bigger plastic container filled with wa-  
 159 ter. In this way the water table was maintained at a level of 6 cm below the soil surface  
 160 leading to the formation of an unsaturated zone of 60% relative moisture content through  
 161 capillary rise (Figure 2a). Cuttings were pruned into four different standard lengths  $L$ : 5,  
 162 10, 15 and 20 cm. The resultant mean diameter of all collected samples,  $\bar{d}$ , was 1.20 cm,  
 163 with a standard deviation,  $\sigma$ , equal to 0.2. Cuttings were allowed to grow roots and stems  
 164 before being uprooted. The lower time limit of growth for the plant to be uprooted was  
 165 set to 2 weeks in order to allow the roots to develop a certain resistance after sprouting.

166 The maximum growth time was 9 weeks (see Table 1). The upper growth limit was dic-  
 167 tated by the state of health of the plant: it has been observed that after 60 days, plants  
 168 were likely to weaken and die. For most alpine rivers, this timescale corresponds to the  
 169 return period of small to moderate floods able to remobilize the logs [Trush *et al.*, 2000].  
 170 No nutrient solution was used to accelerate the growth of the plants. On average, every 4  
 171 days, the following measurements were taken for each cutting: living/dead status, number  
 172 of stems and their combined length, and the number of living leaves. The measurements  
 173 were carried out throughout the lifetime of the plants using a simple ruler (precision 0.1  
 174 cm). The temperature in the laboratory had a mean value of 22°C and a maximal diurnal  
 175 fluctuation of 4°C. Once cuttings had reached their specified growth duration, they were  
 176 extracted from the soil using a motorized pulley system similar to that of *Edmaier et al.*  
 177 [2014] (Figure 3a). For certain samples, the uprooting was obtained under the same mois-  
 178 ture conditions as during the growth phase (60% soil moisture) (Figure 2a), whereas for  
 179 the remaining samples, the water table level was raised to the sediment surface creating a  
 180 saturated medium (Figure 2b). This latter scenario is more representative of conditions to  
 181 which pioneer plants are subjected, and it enables determination of the sediment moisture  
 182 condition applicable to plant uprooting in rivers. Although vertical pullout tests lead to  
 183 overestimation of the root resistance [Coutts, 1983], these tests were nevertheless deemed  
 184 sufficiently reliable to quantify the force required to break the soil-root friction, which,  
 185 when the plant is flexible, is unaffected by the direction of pull [Bankhead *et al.*, 2017]. It  
 186 should be noted that water table fluctuations were not taken into account in these exper-  
 187 iments. Based on the literature (e.g. *Francis et al.* [2005]; *Hughes et al.* [1997]; *Guilloy*  
 188 *et al.* [2011]) and on the control that the water table level exerts on the balance between  
 189 oxygen and water in the soil, it is obvious that the use of different water table depths  
 190 would have affected the biomass evolution of the cuttings, thus adding a further variable  
 191 to the problem.

192 **Table 1.** Summary table listing the length of the cuttings tested, uprooting time, and the total number of  
 193 samples pulled out. Uprooting time refers to the elapsed time between when a cutting is laid on the sediment  
 194 and when it is uprooted.

| cutting size [cm] | uprooting time [weeks] | total samples |
|-------------------|------------------------|---------------|
| 5, 10, 15, 20     | 2, 3, 4, 5, 6, 7, 8, 9 | 326           |

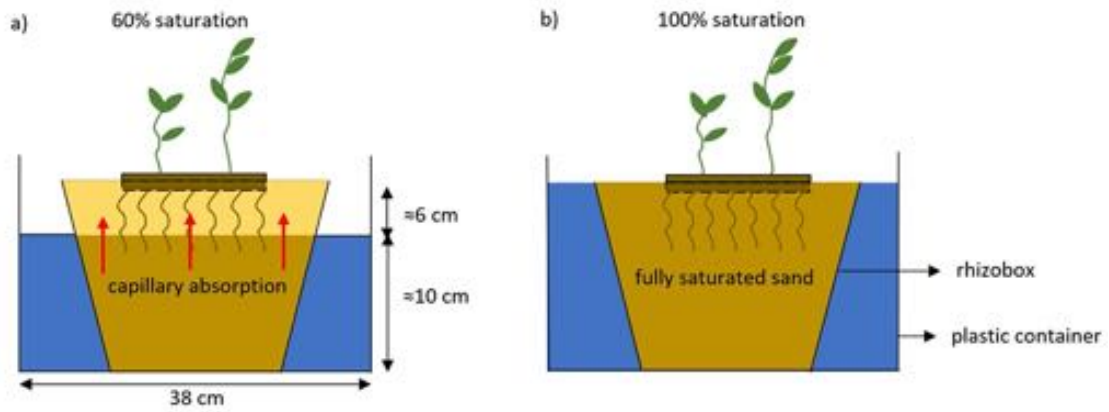


## 2.2 Uprooting Experimental procedure

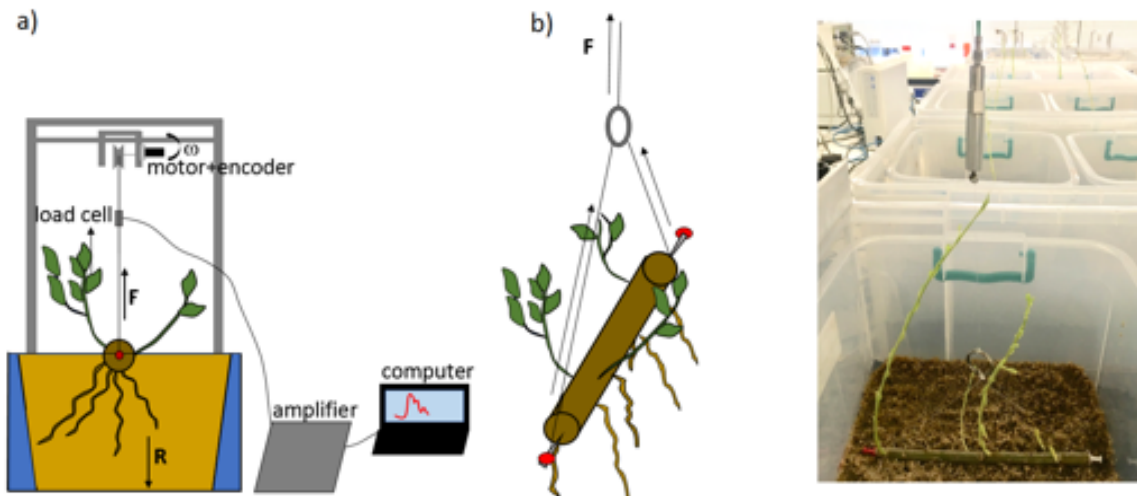
The plant-wire connection system (Figure 3b) was designed to apply direct traction. To achieve this, both extremities of the cutting were clipped to a double loop nylon wire. The loops were tied by means of two drawing pins that had been fixed into the extreme cross-sections during the planting stage to avoid disturbing the later anchorage of the plant. Cuttings were pulled up at constant vertical velocity (1.71 mm/s) by a computer-controlled motor-encoder (EPOS), enabling measurement of the force fluctuations induced by the root system. The vertical uprooting force was recorded at 100 Hz by a piezoelectric force sensor (Kistler) calibrated with a force range of  $\pm 50$  N. The output load cell signal was routed directly to an external charge amplifier (Kistler) that produced an output voltage signal proportional to the mechanical stress (Figure 3a). Measurements of the root architecture parameters were recorded immediately after the samples were uprooted, to avoid inaccuracy from changes to the roots as they lost water content. Roots were gently detached from the log and washed to remove residual soil particles, and then scanned using a EPSON Expression 10000 XL (optical resolution: 2400 dpi). Starting from a predetermined reference point, the relative position of each root along the cutting was assigned an appropriate interval of 1 cm. The small magnitude of the intervals improved the accuracy of the estimated amount of biomass that had grown along the cutting. The root architecture parameters (i.e. root length, volume, surface area) were computed using WinRHIZO BASIC 2009 root analysis software (Régent Instruments Canada, Inc.) for the total root biomass present in each interval.

## 2.3 Statistical analysis

The evolution of the plant biomass was evaluated in terms of sample averages, whose values were fitted to extrapolate growth laws for parameters representing below- and above-ground biomass. Computation of the averages of the root length, number of roots, root surface area, and stem length was undertaken for samples of the same size uprooted within the same week. Trends in average root depth (the average ratio between length and number of roots) and other allometric laws were obtained regardless of the size of the cuttings. A one-sample Kolmogorov-Smirnoff test was carried out to assess whether the observed data on root biomass were uniformly distributed over the normalised cutting lengths. For plants that developed stems (about 65% of the total samples), averaged measurements of



196 **Figure 2.** Sketches of the containers used in the experiments. The plastic box containing the sediment (rhi-  
 197 zoboxes) is stored inside a plastic container filled of water. The rhizoboxes are non-water tight. a) The water  
 198 level is kept about 6 cm below the sediment surface, corresponding to 60% relative moisture of the unsatu-  
 199 rated layer. (This setting was applied to the growth phase of all the plants); b) Soil moisture conditions when  
 200 the samples were uprooted. To achieve 100% saturated soil, the water table level was raised to the surface of  
 201 the sediment.



222 **Figure 3.** Sketch of the pull-out experiment. a) Motorized pulley system whereby the cutting is uprooted  
 223 by an external force powered by a motor whose rotation was measured by an encoder. The exerted force  $\mathbf{F}$   
 224 was continuously recorded by a load cell attached to an amplifier that was connected in turn to a computer.  
 225 The modulus of  $\mathbf{F}$  is equal to the anchoring resistance  $\mathbf{R}$  developed by the root system; b) Schematic view and  
 226 photograph of the plant-wire connection system.

237 total stem length and number of leaves were also computed. Samples that died were dis-  
 238 carded from the statistics, along with plants that did not develop any root system.

239 Sample statistics were obtained of the force drops, and their sequence autocorrela-  
 240 tion extracted from the uprooting curve. Similar procedures were applied to the sequence  
 241 of intertime values between consecutive force drops. This facilitated characterization of  
 242 the statistical nature of the load redistribution mechanism among roots in soil with two  
 243 different values of moisture content.

## 244 **2.4 Drag force model and uprooting by flow**

245 The likelihood of a wood log to experience flow-induced drag and hence possibly  
 246 be removed depends on the topographic elevation above the water level at which the log  
 247 was deposited in relation to the duration and the magnitude of a given flooding event. By  
 248 determining the stream velocity,  $u$ , at a given location and the projected area of the log,  
 249 it is then possible to compute a value for the flow-induced drag force at which plant re-  
 250 moval would occur. In the present computation, we assume a worst-case scenario where  
 251 the impact between the longitudinal cross section of the log and the flow is perpendicular.  
 252 The force components acting on a submerged plant were evaluated following the approach  
 253 proposed by *Bau et al.* [2019], whereby the drag force,  $\mathbf{F}_d$ , is given by the sum of normal  
 254  $\mathbf{F}_{d,n}$  and tangential  $\mathbf{F}_{d,t}$  force components, such that

$$\mathbf{F}_d = \mathbf{F}_{d,n} + \mathbf{F}_{d,t} \quad (1)$$

255 The modulus of  $\mathbf{F}_{d,n}$  is:

$$F_{d,n} = \frac{1}{2} C_d \rho_w u^2 A_n, \quad (2)$$

256 where  $C_d$  is the drag coefficient,  $u$  is the approach flow velocity impacting the log and  $A_n$   
 257 the projected area of the trunk of the log in the flow direction. The modulus of  $\mathbf{F}_{d,t}$  was  
 258 calculated as:

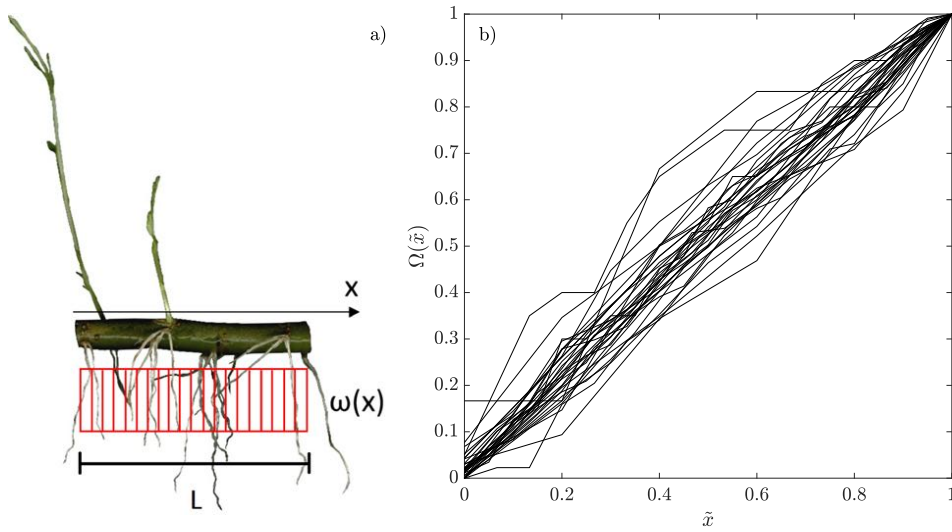
$$F_{d,t} = \frac{1}{2} C_f \rho_w u^2 (A_s + A_l), \quad (3)$$

259 where  $C_f$  is the friction coefficient,  $A_s$  is the total surface area of the stems, and  $A_l$  is  
 260 the total area of the leaves exposed to the flow. To calculate the projected and surface ar-  
 261 eas  $A_n$ ,  $A_s$  and  $A_l$ , the trunk, stem, and leaves were approximated by simple geometric  
 262 shapes: a rectangle, a cylinder, and rhombus, respectively (see *Bau et al.* [2019]).  $C_d$  and  
 263  $C_f$  were each assigned a representative value of 1 [*Järvelä*, 2002].

### 3 Results

#### 3.1 Below- and above-ground biomass

The scanned image of a generic cutting after uprooting (Figure 4a) shows that the root biomass per unit length,  $\omega(x)$ , is almost uniformly distributed over the distance coordinate  $x$ . This observation is confirmed by considering the variation in normalized cumulative sum of the total root surface area,  $\Omega(\tilde{x}) = \int_0^{\tilde{x}} \omega(\xi) d\xi$ , with normalised cutting length,  $\tilde{x} = \frac{x}{L}$  (Figure 4b). The normalised cumulative sum profiles shown in Figure 4b are plotted for all growth stages and all cutting sizes. Results from the one-sample Kolmogorov-Smirnoff test showed that the null hypothesis was never rejected for a significance level equal to 0.05, implying that the empirical distribution functions are statistically close to the uniform density distribution. This indicates that the logs tend to develop roots at a constant spatial distance independent of their size, which is relevant for upscaling purposes. Figure 5a summarizes the growth statistics obtained for the different cuttings. Fig-



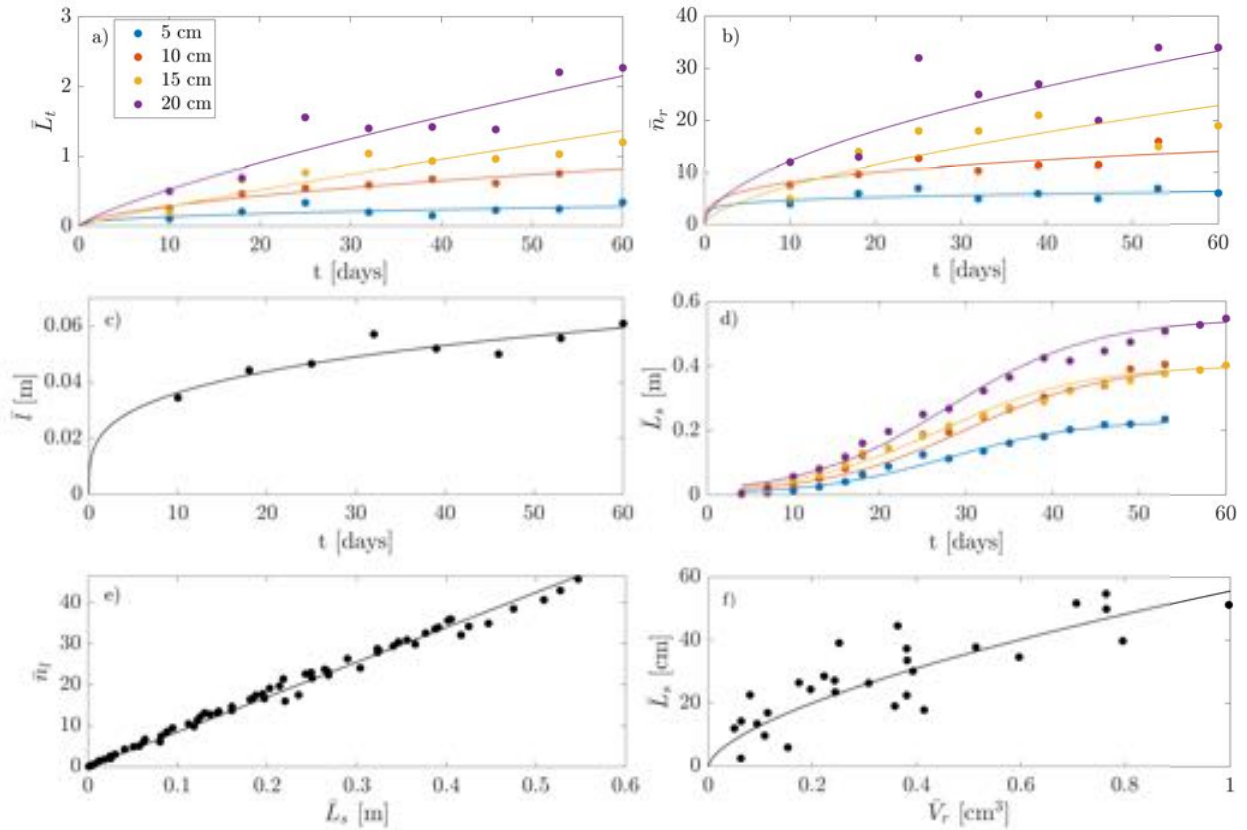
**Figure 4.** a) Coloured scanned image of a sample of length  $L$ . (red bars highlight the uniform distribution of the root biomass over the distance coordinate  $x$ ); b) normalized cumulative sums of the total root surface area of the samples versus normalized cutting length.

ure 5a shows that the growth trends of the root lengths tend to follow power laws of the form  $\bar{L}_r = c_1 \cdot t^{d_1}$ . Similar trends emerge in Figure 5b, which depicts the variation in

282 averaged number of roots,  $\bar{n}_r$ , with time. Average values of the number of roots were cal-  
 283 culated following the same approach used for the total root length, and the results fitted to  
 284 equations of the form:  $\bar{n}_r = c_2 \cdot t^{d_2}$ . Table 2 lists the fitting coefficients and the goodness  
 285 of fit measures,  $R^2$ , for both power laws. After determining  $\bar{L}_r$ ,  $\bar{n}_r$ , and the uniform dis-  
 286 tribution of the roots with  $x$  (Figure 4), it was then possible to evaluate the average root  
 287 depth,  $\bar{l}$ . Once again, the power law is most suitable to describe the trend in average root  
 288 depth over time:  $\bar{l} = c_3 \cdot t^{d_3}$  (Figure 5c). Table 3 lists the resulting values for  $c_3$  and  $d_3$ .  
 289 Figure 5d shows the variation of the averaged total length of the stems,  $\bar{L}_s$ , with time for  
 290 each size class. The trend followed by the data points suggests that a logistic curve would  
 291 be suitable to describe plant growth limited by carrying capacity, here represented by the  
 292 internal nutrient reserves of the wood log [Schimpf *et al.*, 1977; Hsu *et al.*, 1984]. The lo-  
 293 gistic curve for averaged total length of stems is:

$$\bar{L}_s(t) = \frac{\bar{L}_{s,max}}{1 + e^{-b(t-t_0)}} \quad (4)$$

294 where  $\bar{L}_{s,max}$  is the curve's maximum value which coincides with the averaged total stem  
 295 length recorded in the last growth range,  $b$  is the logistic growth rate and  $t_0$  is the loca-  
 296 tion of the midpoint of the sigmoid. To achieve the best fit, the value of  $b$  was set equal  
 297 to 0.12 independent of  $L$ ,  $t_0$  was located at 28 for both  $L=5$  cm and  $L=20$  cm, and at 30  
 298 and 27 for  $L=10$  cm and  $L=15$  cm, respectively. The equation predicted that stems grow  
 299 to a maximum value corresponding to the carrying capacity of the logistic model. The  
 300 maximum average total stem length generally increases progressively with  $L$ , the size of  
 301 the cutting (Figure 5d), except for plants with  $L=10$  cm, whose maximum value is slightly  
 302 above that reached by plants of size 15 cm, possibly due to experimental noise effects.  
 303 Figure 5e displays how the average number of leaves  $\bar{n}_l$  correlates linearly with  $\bar{L}_s$ . Here  
 304 data are fitted by a regression line of the form:  $\bar{n}_l = c_4 \cdot \bar{L}_s$ . Figure 5f shows the cor-  
 305 relation between the total length of the stems and the total root volume developed by the  
 306 time of uprooting. However, owing to the high variability of data, the stem length and the  
 307 root volume were represented by mean values,  $\bar{L}_s$  and  $\bar{V}_r$ , computed for all samples at the  
 308 same growth stage. In this case, data follow a power law with equation:  $\bar{L}_s = c_5 \cdot \bar{V}_r^{d_5}$ .  
 309 A similar fitting law was also obtained in a previous experimental study [Pasquale *et al.*,  
 310 2014]. Table 3 lists the fitted coefficients for  $\bar{n}_l$  and  $\bar{L}_s$ .



311 **Figure 5.** Average trends in below-ground parameters: a) variation in average total root length with time  
 312 for different size of cuttings; b) variation in average root number with time for different sizes of cuttings; c)  
 313 variation in average root depth over time; d) trends in average value of the total stem length with time for each  
 314 cutting size; e) average number of leaves with averaged total length of the stems; and f) average total stem  
 315 length versus averaged root volume.

### 319 3.2 Resistance to uprooting

320 The force-displacement signals illustrated in Figure 6 show the anchorage ability  
 321 of roots to withstand a vertical pulling force. In general, the force-displacement curve  
 322 comprises three main phases, as identified in previous studies [Edmaier *et al.*, 2011; En-  
 323 nos, 1989]. The first phase is a non-linear elastic phase, during which the force increases  
 324 non-linearly with elastic recovery. The second phase presents linear elastic behaviour until  
 325 maximum uprooting resistance is achieved. This quantity corresponds to the highest value  
 326 of the tensile force that the root system can withstand. The third phase is the descending  
 327 process, where the force decline occurs as a sequence of drops and partial elastic recov-  
 328 eries until uprooting is entirely achieved. This last phase is the result of the progressive

316

**Table 2.** Fitting coefficients and goodness of fit  $R^2$  for power laws fitting  $\bar{L}_r$  and  $\bar{n}_r$ .

| cutting size | $\bar{L}_r$ [m] |       |       | $\bar{n}_r$ [-] |       |       |
|--------------|-----------------|-------|-------|-----------------|-------|-------|
|              | $c_1$           | $d_1$ | $R^2$ | $c_2$           | $d_2$ | $R^2$ |
| 5 cm         | 0.05            | 0.41  | 0.41  | 3.19            | 0.17  | 0.28  |
| 10 cm        | 0.08            | 0.58  | 0.92  | 4.08            | 0.30  | 0.64  |
| 15 cm        | 0.04            | 0.88  | 0.81  | 1.78            | 0.62  | 0.69  |
| 20 cm        | 0.08            | 0.81  | 0.88  | 3.38            | 0.56  | 0.66  |

317

**Table 3.** Fitting coefficients and goodness of fit  $R^2$  for power laws fitting  $\bar{l}$  and  $\bar{L}_s$  and the linear law fitting

318

 $\bar{n}_l$ . For these parameters, the fitting equations are independent of the size of the cuttings.

| $\bar{l}$ [m] |       |       | $\bar{n}_l$ [-] |       |       | $\bar{L}_s$ [cm] |       |       |
|---------------|-------|-------|-----------------|-------|-------|------------------|-------|-------|
| $c_3$         | $d_3$ | $R^2$ | $c_4$           | $d_4$ | $R^2$ | $c_5$            | $d_5$ | $R^2$ |
| 0.02          | 0.27  | 0.85  | 85              | -     | 0.97  | 55.58            | 0.63  | 0.60  |

329

release of roots from the soil [Bailey *et al.*, 2002; Mickovski *et al.*, 2007] and from root

330

loosening [Smith, 2007]. These three different phases are obvious in several of the uproot-

331

ing curves shown in the panels in Figure 6. In previous studies, the maximum root resis-

332

tance exerted by roots was found to increase with total root length [Bywater-Reyes *et al.*,

333

2015; Ennos, 1989; Bailey *et al.*, 2002; Karrenberg *et al.*, 2003; Edmaier *et al.*, 2014].

334

The same trend is observed in the present data (Figure 7), where the maximum uproot-

335

ing force,  $F_{max}$ , increases linearly with the total root length of the samples,  $L_r$ , depending

336

on soil water content [Pollen, 2007; Pollen-Bankhead and Simon, 2010]. The uprooting

337

force increases also with time, as can be seen by the relationship between the total root

338

length and time depicted in Figure 5a. Moreover, it can be observed that the maximum

339

uprooting force simply depends on the size of the cutting expressed by the total rooting

340

length, which in turn, scales with the cutting size  $L$ . This confirms the existence of a pos-

341

sible upscaling law (given the low variability of the cutting diameters). By comparing

342

Figure 7a and 7b, it is also clear how, in fully-saturated conditions (Figure 7a), the max-

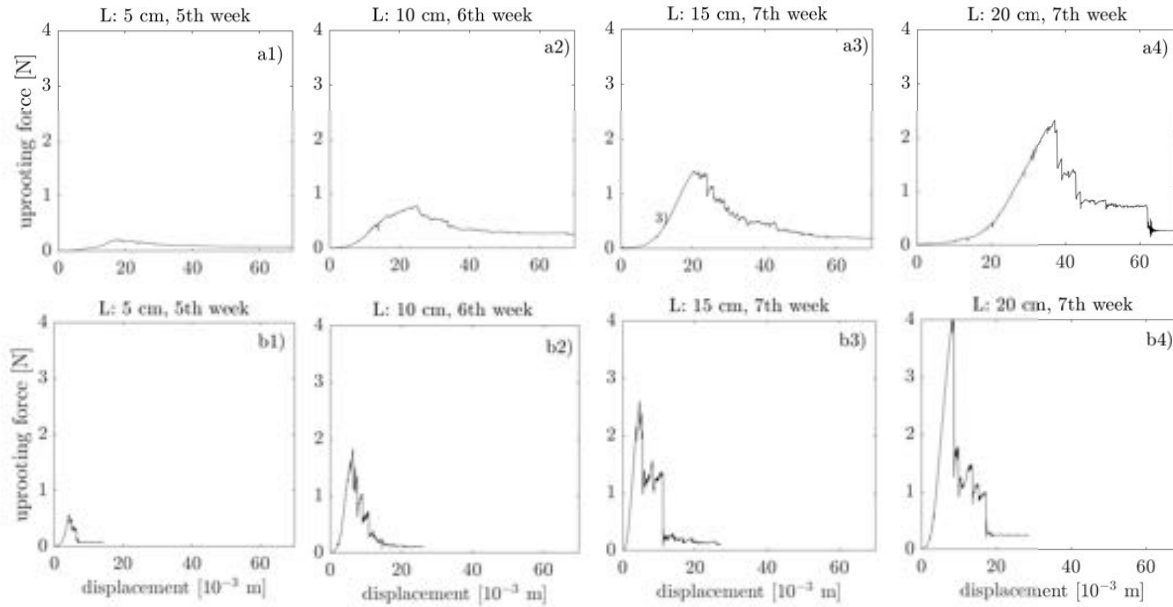
343

imum uprooting force is more than about twice lower than the force exerted in unsaturated

344

conditions (Figure 7b). An explanation of this phenomenon is provided by Wood [1990]

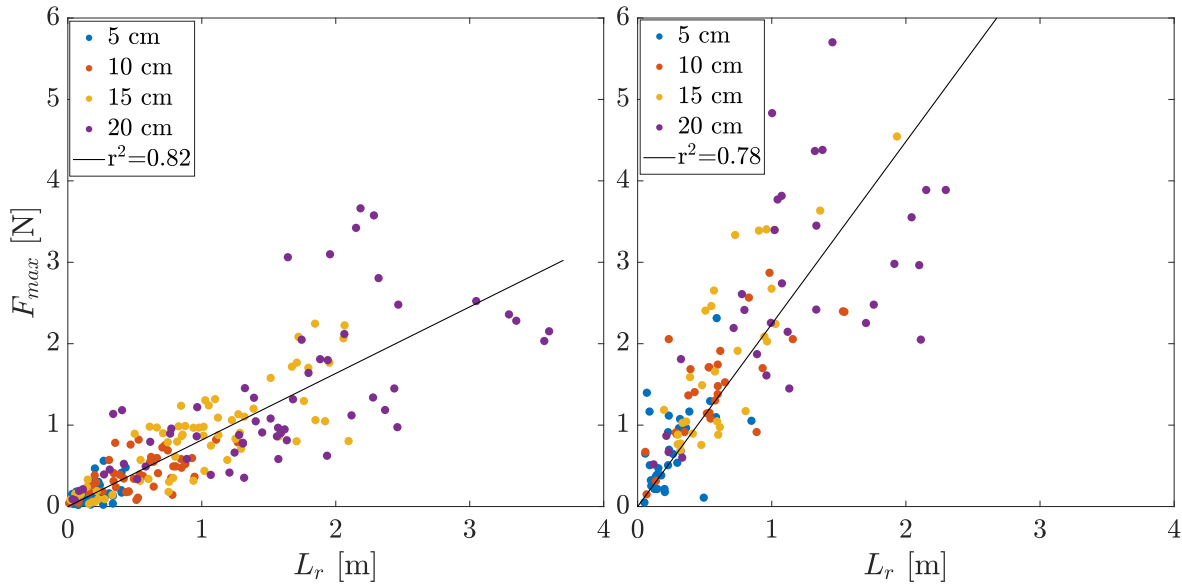
345 who argues that undrained stress in saturated soil increases pore-water pressure, causing  
 346 the frictional strength of the soil to reduce. In turn, this mechanism may enhance the slid-  
 347 ing of roots among the sediment particles. To explain why this significant difference in  
 348 maximum uprooting force occurs under different saturation conditions, we examine the  
 349 force-displacement curves in Figure 6.



350 **Figure 6.** Force-displacement curves for *Salix* cuttings of different size  $L$  uprooted at different times. Sam-  
 351 ples illustrated in panels a) were uprooted under 100% saturation conditions, whereas the others in b) were  
 352 uprooted under 60% saturation. The panels are arranged in terms of cutting size  $L$  and sample uprooting time  
 353 as follows: a1)  $L=5$  cm and week= $5^{th}$ ; a2)  $L=10$  cm, week= $6^{th}$ ; a3)  $L=15$  cm, week= $7^{th}$ ; a4)  $L=20$  cm,  
 354 week= $7^{th}$ ; b1)  $L=5$  cm and week= $5^{th}$ ; b2)  $L=10$  cm, week= $6^{th}$ ; b3)  $L=15$  cm, week= $7^{th}$ ; b4)  $L=20$  cm,  
 355 week= $7^{th}$ .

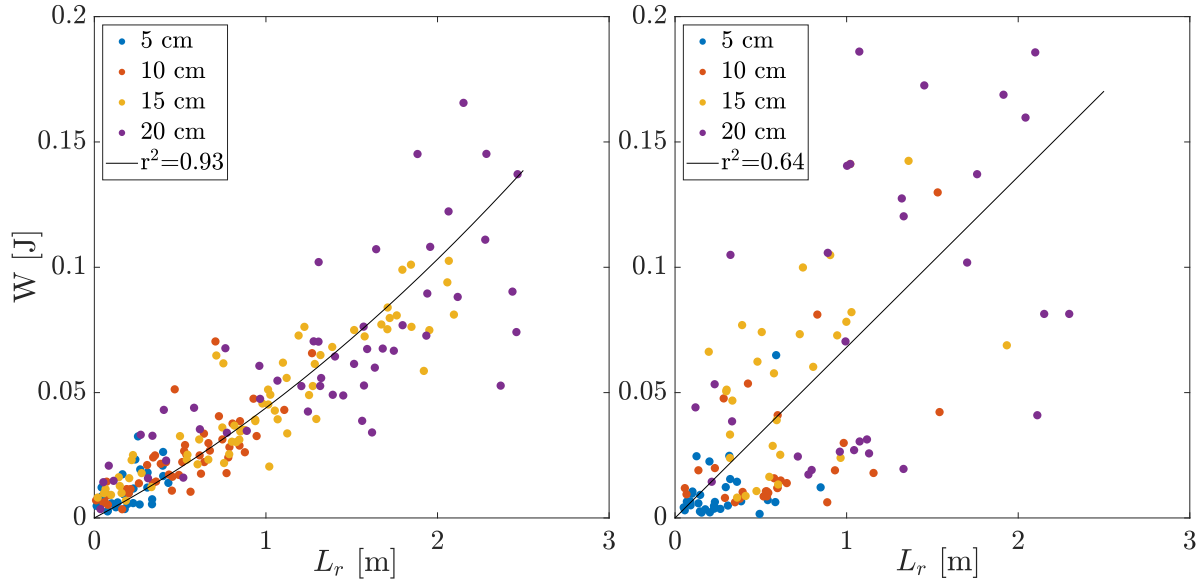
364 Figure 6 not only shows that the maximum force peak reaches higher values under  
 365 low saturated conditions, but also illustrates some differences in the descending phase.  
 366 Typically, in sand of low saturation, the anchoring force decays rapidly, with large and  
 367 rapid drops following sharp peaks. The trend is more discernible for 20 cm cuttings and  
 368 less evident as the size of the cuttings diminishes because the load that the plant is re-  
 369 quired to withstand is smaller. For saturated sand, the descending phase is slower and  
 370 smoother indicating more uniform friction, with smaller post-peak force oscillations. Sim-  
 371 ilar behaviour was observed by other authors [Ennos, 1990; Schwarz *et al.*, 2011; Edmaier





356 **Figure 7.** Maximum uprooting force plotted against the total root length. a) 100% saturated medium, with  
 357 linear fitting law given by  $F_{max}=0.82 \cdot L_r$  with goodness of fit  $R^2=0.67$  and Pearson coefficient  $r^2=0.82$ ; b)  
 358 60% saturated medium, with linear fitting law given by  $F_{max}=2.24 \cdot L_r$  with goodness of fit  $R^2=0.54$  and  
 359 Pearson coefficient  $r^2=0.78$ .

372 *et al.*, 2014] and will be further discussed in the following sections. Uprooting work done  
 373 (Figure 8), evaluated by computing the area under the force-displacement curve, reveals  
 374 valuable information about the resilience to uprooting of the plant. For 100% sediment  
 375 moisture content (Figure 8a), the uprooting work done is well approximated by a second  
 376 degree polynomial law, whereas for a plant uprooted from low saturated sand (Figure 8b)  
 377 the work done increases linearly with total rooting length albeit with higher variability.  
 378 These two different trends in uprooting work done may be explained by examining the  
 379 post-peak phase of the force-displacement curve in Figure 6, where the major portion of  
 380 the work done is undertaken. By comparing Figure 6a and 6b it can be seen that the up-  
 381 rooting process requires more time in sand that is fully-saturated than under conditions  
 382 of low-saturation when roots have less resilience because of energy loss occurring over  
 383 shorter time and space scales.

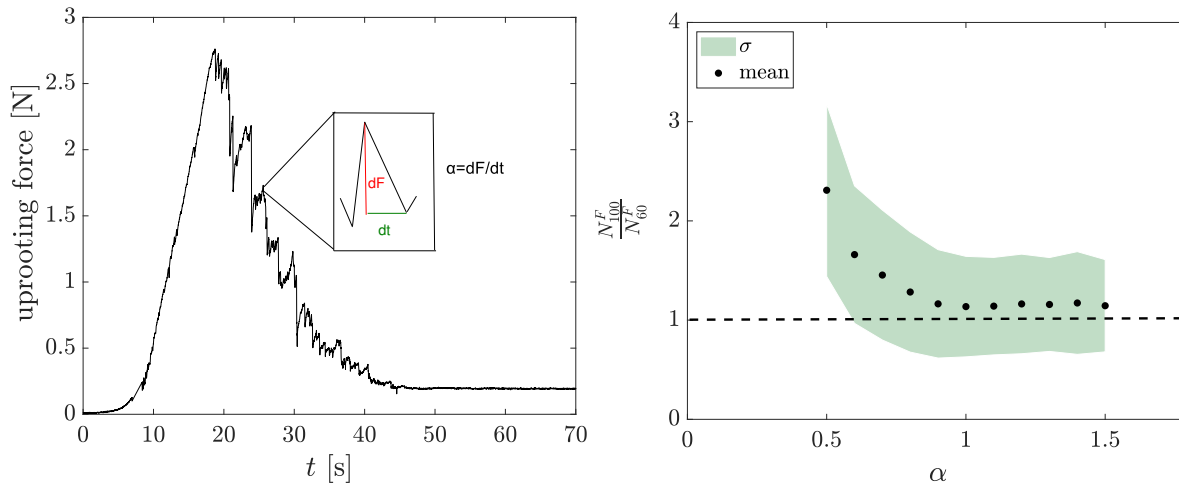


360 **Figure 8.** Variation in maximum uprooting work done with total root length: a) 100% saturated medium,  
 361 where the fitting law is quadratic,  $W=8 \cdot 10^{-7} L_r^2 + 4 \cdot 10^{-4} L_r$ , with goodness of fit  $R^2=0.83$  and correlation  
 362 coefficient (Spearman coefficient)  $r^2=0.93$ ; and b) 60% saturated medium, where the fitting law is linear,  
 363  $W=7 \cdot 10^{-4} L_r$ , with goodness of fit  $R^2=0.41$  and Pearson coefficient  $r^2=0.64$ .

### 384 3.3 Force drop analysis

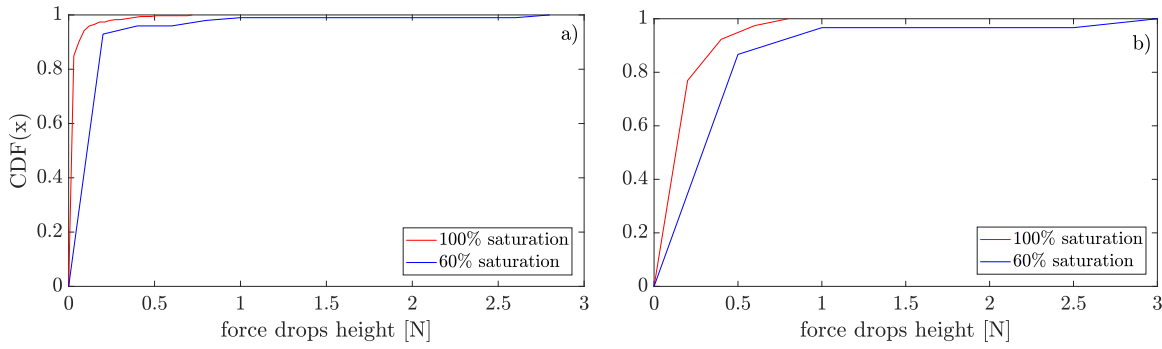
385 Before performing a statistical analysis of force drops, we first define the term 'force  
 386 drop' and then present a quantitative method for classifying force drops. A force drop cor-  
 387 responds to a monotonic decline in force-time signal between two successive local maxi-  
 388 mum and minimum values. Given that the monotonic decline has a certain mean gradient,  
 389 we introduce a parameter that represents the steepness of the force drops and can be used  
 390 for their classification. The force drop parameter,  $\alpha$ , is expressed as the ratio between the  
 391 local maximum-to-minimum differences between two consecutive force values  $dF$  and  
 392 their respective time-lapses  $dt$  (Figure 9a). By varying  $\alpha$ , the force drops can be classified  
 393 according to size and number. Figure 9b shows the variation in ratio of number of force  
 394 drops in 100% saturated soil,  $N_{100}^F$ , to that in 60% saturated soil,  $N_{60}^F$ , with  $\alpha$ . Values for  
 395  $N_{100}^F$  and  $N_{60}^F$  were obtained by computing the average numbers of force drops determined  
 396 from force signals for plants uprooted at the same time in saturated and unsaturated condi-  
 397 tions. Figure 9b shows that the ratio  $\frac{N_{100}^F}{N_{60}^F}$  decreases exponentially for  $\alpha \geq 0.5-0.9$  and be-  
 398 comes independent of  $\alpha$  when  $\alpha$  is close to 1. This leads us to deduce that mild drops oc-

399 cur more frequently when plants are uprooted from saturated soil. However, the proportion  
 400 of steep drops is the same regardless of the water sediment content. Figure 10 illustrates  
 401 the cumulative relative frequencies of force drops magnitude computed for plants of similar  
 402 root length that are uprooted at the same time under two different sediment moisture  
 403 conditions, corresponding to Figures 6a4 and 6b4. For  $\alpha \geq 0.5$  (Figure 10a), 50% of the  
 404 force drops of a plant uprooted from saturated sediment have magnitude less than 0.017  
 405 N, far below the value of 0.107 N obtained for a plant pulled out from low saturated sed-  
 406 iment. For the same value of  $\alpha$ , the force drops exhibit a magnitude up to 4 times larger  
 407 in 100% saturated sediment, than in low saturated sand. A similar trend is observed for  
 408  $\alpha \geq 1.5$  (Figure 10b). This finding that the magnitude of force drops is higher for less  
 409 saturated sediment implies stronger adhesion among sediment particles in such cases [Ed-  
 410 maier *et al.*, 2011].



411 **Figure 9.** Relationship between uprooting force with time and force drop ratio with  $\alpha$  a) generic force-  
 412 displacement curve illustrating the concepts of  $dF$ ,  $dt$  and  $\alpha$ ; and b) variation in averaged ratio between the  
 413 number of force drops in 100% saturated soil to that in 60% saturated soil with  $\alpha$ , displaying mean values  
 414 (dots) and standard deviation  $\sigma$  (green shading).

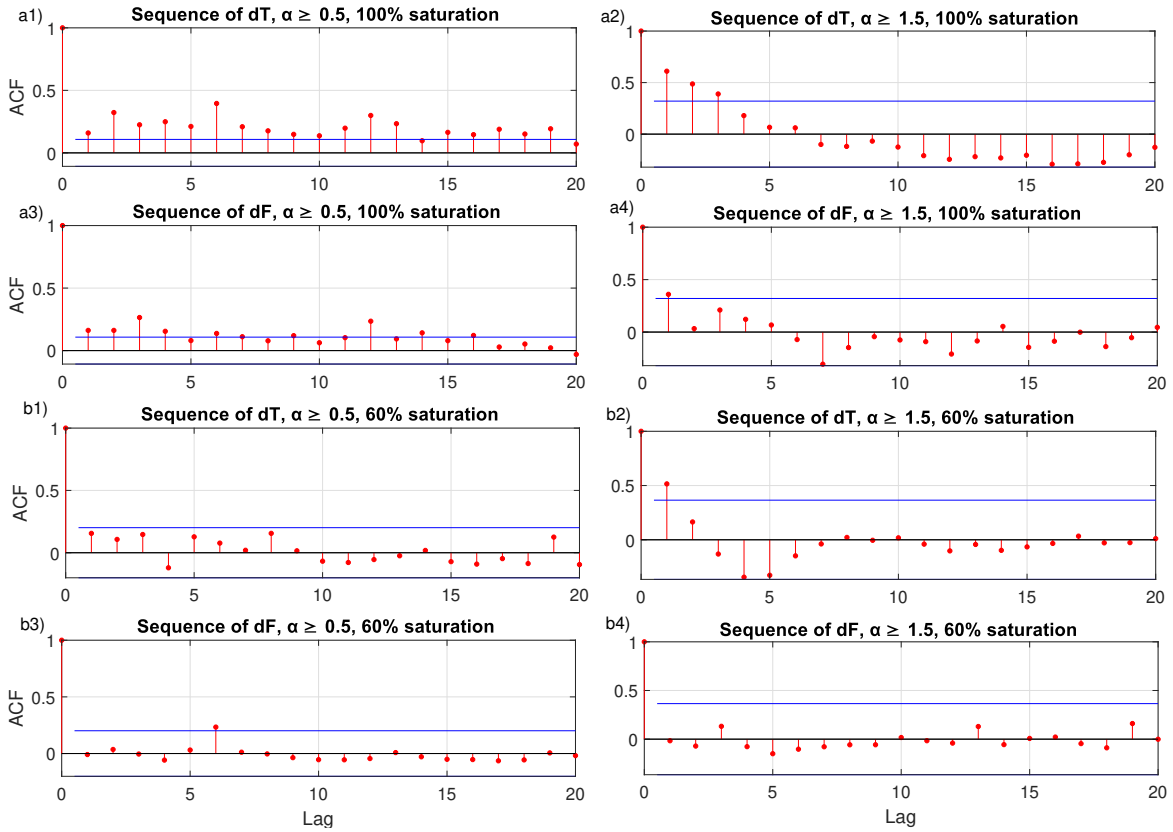
417 Therefore, regardless of the magnitude of the force drop sequence, the mechanism  
 418 controlling downward jumps changes according to the moisture level of the sediment. It  
 419 is also instructive to compare the autocorrelation function of the  $dF$  sequence and the  
 420 force drops intertime  $dT$  sequence. For 100% saturation and  $\alpha \geq 0.5$ , the autocorrelo-  
 421 grams of the force drop and intertime sequences exhibit positive, though low, correlations



415 **Figure 10.** Cumulative relative frequencies of the force drops corresponding to the force-displacement  
 416 curves in Figure 6a4 (100% saturation) and Figure 6b4 (60% saturation) when: a)  $\alpha \geq 0.5$ ; b)  $\alpha \geq 1.5$ .

422 for almost every lag (Figures 11a1 and 11a3). This is most likely due to rearrangement  
 423 of sand grains in the soil matrix when roots are sliding. In low saturated conditions (Fig-  
 424 ures 11b1 and 11b3), the correlation is not significant. This discrepancy may be explained  
 425 as follows: when the medium is entirely saturated, water fills the pores and roots tend to  
 426 slide between the sand grains. The presence of water modifies the sand grain arrangement  
 427 around the roots, and causes regular force decay to occur [Schwarz *et al.*, 2011]. Con-  
 428 versely, when the water content in the sediment is lower (60% of water content), the force  
 429 signal (Figure 6b) presents steeper force drops (steep loosening). Once roots exceed the  
 430 soil strength, the lower cohesion of sand allows quicker movement of the roots through the  
 431 grains. Thus, the force drops and their related intertimes assume an autocorrelated 'white'  
 432 noise structure. Moreover, the large force drops and the related intertimes appear to have  
 433 a correlation structure with a spatial scale comparable to the smallest fluctuation in the  
 434 process, i.e. of the order of the sediment grains [Crouzy *et al.*, 2014].

443 We now analyse the final force recovery event in the force-displacement signal,  $F_{res}$ ,  
 444 and compare it to  $F_{max}$  (see Figure 12). In the scatter plots in Figure 12, two main re-  
 445 gions can be identified. The first region, to the left of the green line, includes mostly  
 446 small cuttings of which some of the less mature 15-20 cm cuttings have invested all their  
 447 energy in withstanding the uprooting force. Notably, for fully-saturated soil, the data in  
 448 the left region are dispersed within a range of  $\frac{F_{res}}{F_{max}}$  that is larger than in low-saturated  
 449 medium. This agrees with the trends in descending phases observed in Figure 6. In 60%  
 450 saturated soil, the energy loss occurs with large force drops and over shorter time inter-  
 451 vals than in 100% saturated soil. This implies that the residual energy of roots may not be

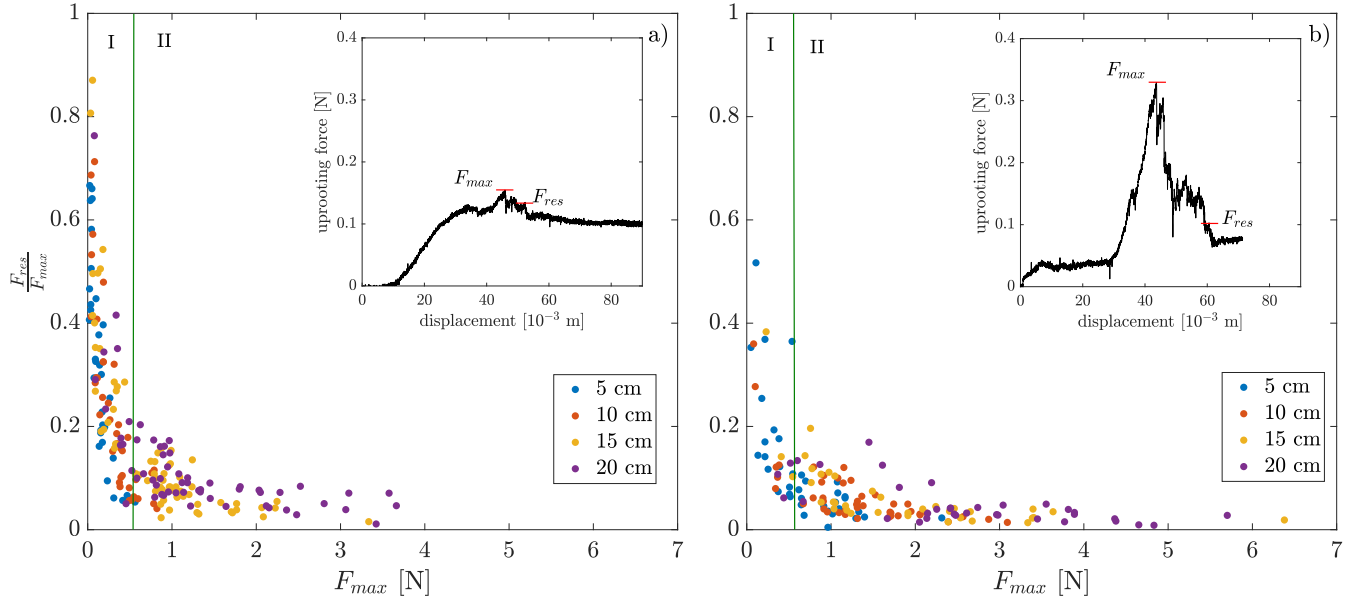


435 **Figure 11.** Autocorrelation functions of the force drops  $dF$  and their respective intertime  $dT$ . The blue  
 436 solid lines demark confidence bounds. Autocorrelation of the force drops intertime  $dT$  for 100% saturation  
 437 when: a1)  $\alpha \geq 0.5$ ; a2)  $\alpha \geq 1.5$ ; Autocorrelation of the force drops  $dF$  for 100% saturation when: a3)  $\alpha \geq 0.5$ ;  
 438 a4)  $\alpha \geq 1.5$ . Autocorrelation of the force drops intertime  $dT$  for 60% saturation when: b1)  $\alpha \geq 0.5$ ; b2)  
 439  $\alpha \geq 1.5$ ; Autocorrelation of the force drops  $dF$  for 60% saturation when: b3)  $\alpha \geq 0.5$ ; b4)  $\alpha \geq 1.5$ .

452 sufficient to generate a resistance  $F_{res}$  comparable to  $F_{max}$ . Region II includes cuttings  
 453 uprooted at a later stage of growth, when  $\frac{F_{res}}{F_{max}}$  is almost constant regardless of the value  
 454 of  $F_{max}$ . The presence of mature plants in the right hand region indicates that older plants  
 455 can have higher resilience. A similar division of  $\frac{F_{res}}{F_{max}}$  data into two regions with respect  
 456 to  $F_{max}$  was also observed by *Crouzy et al.* [2014] for *Avena sativa* plants.

#### 457 **4 Uprooting by flow**

458 Plant uprooting by flow occurs whenever the action of the drag and the net buoy-  
 459 ancy forces equal the root resistance exerted by total root length of the plant  $\mathbf{R}(L_r)$  [*Ed-*



440 **Figure 12.**  $\frac{F_{res}}{F_{max}}$  versus  $F_{max}$  for uprooting in: a) 100% saturation soil; b) 60% saturated soil. The inset  
 441 panels comprise force-displacement curves on which are marked the maximum uprooting force  $F_{max}$  and the  
 442 residual force  $F_{res}$  at which failure of the last plant fiber occurs.

460 *maier et al.*, 2014]. The force may be expressed as:

$$\mathbf{F}_{d,n} + \mathbf{F}_{d,t} + \mathbf{F}_n = \mathbf{R}(L_r), \quad (5)$$

461 where  $\mathbf{F}_{d,n}$  is the normal component of the drag force,  $\mathbf{F}_{d,t}$  is the tangential component of  
 462 the drag force, and  $\mathbf{F}_n$  is the net buoyancy force. When the root resistance  $\mathbf{R}(L_r)$  equals  
 463 the pulling force  $\mathbf{F}_{max}$  for an equal root length in static conditions, equation (5) reads:

$$\mathbf{F}_{d,n} + \mathbf{F}_{d,t} + \mathbf{F}_n = \mathbf{F}_{max}(L_r), \quad (6)$$

464 where  $\mathbf{F}_{max}(L_r)$  relates to the fitting law extrapolated under saturated conditions (Figure  
 465 7a), such that:

$$F_{max} = 0.82 \cdot L_r \quad (7)$$

466 Herein, the net buoyancy force  $\mathbf{F}_n$  is neglected, following previous studies [*Bywater-Reyes*  
 467 *et al.*, 2015; *Calvani et al.*, 2019; *Bau et al.*, 2019]. From a graphical perspective, uproot-  
 468 ing takes place when the drag surpasses the root maximum resistance curve. In order to  
 469 be able to plot the drag force and the resistance law, the drag force is expressed as a func-  
 470 tion of the total root length  $L_r$ . Hence, it is necessary to express both the total surface

471 area of the stem  $A_s$  and the total projected area of the leaves  $A_l$ , which appear in the  
 472 modulus of  $\mathbf{F}_{d,t}$  (equation 3), in terms of  $L_r$ . The total surface area of the stem is given  
 473 by:

$$A_s = \pi d_s \left( \frac{\bar{L}_{s,max}}{1 + e^{[-b((\frac{L_r}{c_1})^{\frac{1}{d_1}} - t_0)]}} \right) \quad (8)$$

474 where  $d_s$  is the diameter of the cylinder, and the expression in parenthesis is the logistic  
 475 curve (equation 4) rewritten in terms of  $\bar{L}_r$  by invoking the link between time and the av-  
 476 eraged root length extrapolated from Figure 5a. The projected area of the leaves is given  
 477 by:

$$A_l = \frac{d_L d_l}{2} \left[ c_4 \left( \frac{\bar{L}_{s,max}}{1 + e^{[-b((\frac{L_r}{c_1})^{\frac{1}{d_1}} - t_0)]}} \right) \right] \quad (9)$$

478 where  $d_L$  and  $d_l$  are the length of the two diagonals of the rhombus and the term in square  
 479 brackets is obtained using the correlation law between the number of leaves and the stem  
 480 length extrapolated from Figure 5e. The projected area  $A_n$  of the trunk that appears in the  
 481 expression of the normal component of the drag force (equation 2) depends linearly on the  
 482 size of the cutting  $L$ :

$$A_n = \frac{L\bar{d}}{2} \quad (10)$$

483 Under the reasonable assumption that  $\bar{L}_r \approx L_r$ , the modulus of the drag force can be  
 484 expressed as follows:

$$F_d = \frac{1}{2}\rho C_d u^2 \frac{L\bar{d}}{2} + \frac{1}{2}\rho C_f u^2 \left[ \pi d_s \left( \frac{\bar{L}_{s,max}}{1 + e^{[-b((\frac{L_r}{c_1})^{\frac{1}{d_1}} - t_0)]}} \right) + \frac{d_L d_l}{2} c_4 \left( \frac{\bar{L}_{s,max}}{1 + e^{[-b((\frac{L_r}{c_1})^{\frac{1}{d_1}} - t_0)]}} \right) \right] \quad (11)$$

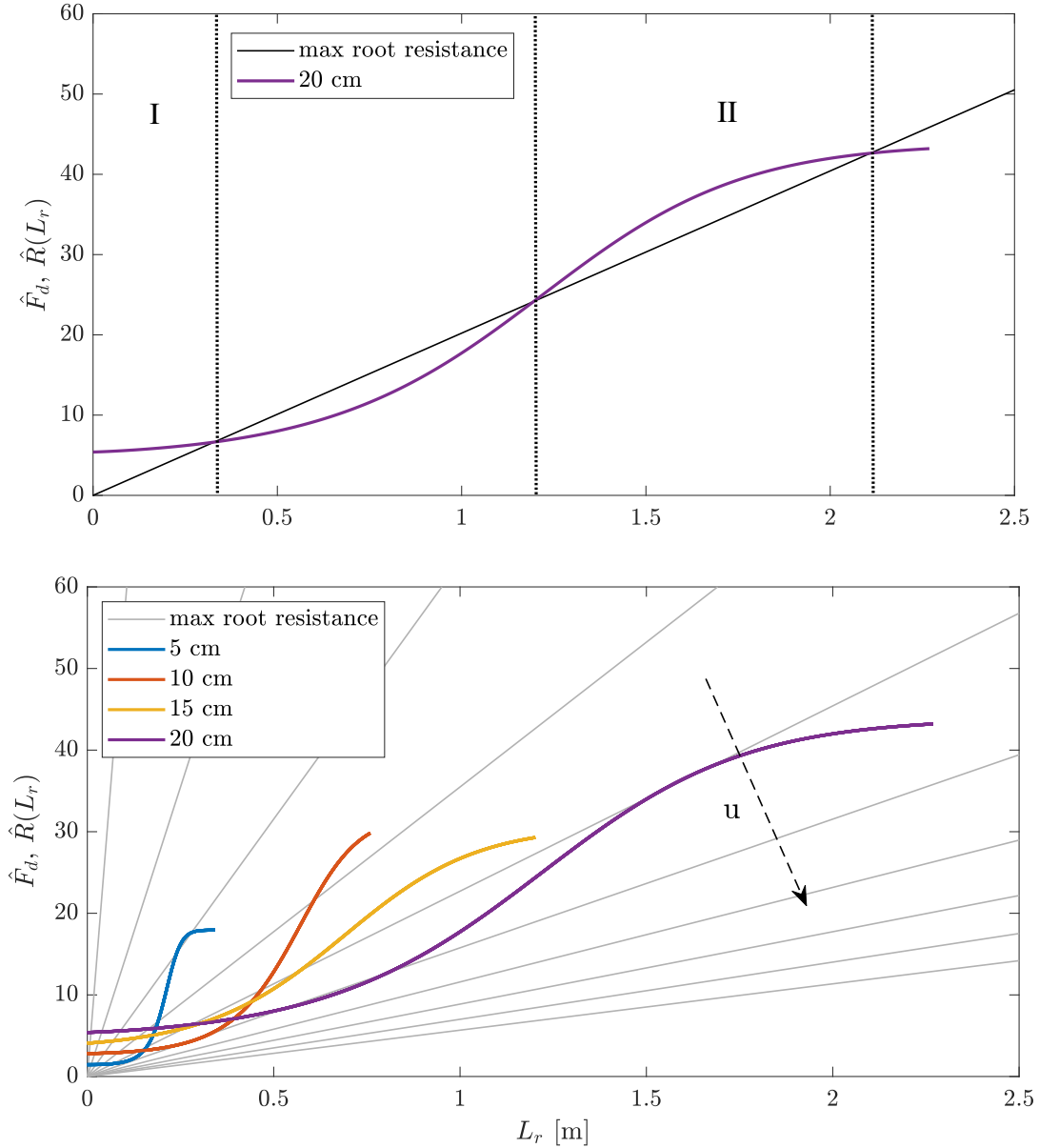
485 Figure 13a displays the trends in dimensionless drag force,  $\hat{F}_d$ , and maximum root resis-  
 486 tance,  $\hat{R}(L_r)$ , with increasing  $L_r$ . The plot refers to a cutting with  $L=20$  cm and a fixed  
 487 value of  $u$ . The dimensionless forms were obtained by dividing equations 7 and 11, re-  
 488 spectively, by the product:  $\rho^{\frac{1}{2}} C_f u^2 \bar{d}^2$ , such that the drag force is parametrized by  $L$ ,  
 489 whereas the root resistance scales with  $u$ . It is obvious that uprooting occurs within two  
 490 temporal windows. The first one, I, is located at the very early stage of plant growth when  
 491 the root length is still small and the curve of the drag forces is convex. The second win-  
 492 dow, II, occurs in the section of the curve that coincides with the terminal growth stage of  
 493 the plants. The occurrence of biological time windows is reminiscent of a concept intro-  
 494 duced by *Balke et al.* [2011], who studied the threshold for the establishment of mangrove  
 495 seedling on tidal flats. Figure 13b shows the trend in dimensionless drag force with root  
 496 length  $L_r$  for all values of cutting length  $L$ . Here,  $\hat{R}(L_r)$  is plotted for increasing values

497 of  $u$  (grey lines). The  $\hat{F}_d$  curves cross the  $L_r=0$  axis at different ordinate values. This is  
498 because when wood logs have not yet developed any above- and below- ground biomass,  
499 the drag force acts only on the portion of the trunk exposed to the flow. Over a certain  
500 range of low flow velocities, wood logs can provide resistance to drag forces without any  
501 contribution from root resistance. Importantly, this means that the present model is appli-  
502 cable both to species able to reproduce asexually, and to species incapable of resprouting.  
503 Figure 13b also shows that drag force curves interrupt at values of  $L_r$  that increase pro-  
504 gressively with  $L$ . Unlike the root resistance curve, the trend in drag force is therefore  
505 affected by the size of the cuttings.

## 508 **5 Discussion**

509 Although previous studies documented the importance of studying wood regime dy-  
510 namics in river basins, a full understanding was not developed as to how the biomechan-  
511 ical properties of regenerated living wood impact its remobilization. In the present study,  
512 we examine the anchoring resistance and the growth performance of small-scale logs of  
513 *Salix fragilis*, a species that colonizes wide areas along rivers and spreads through vege-  
514 tative reproduction. Our results confirm that knowledge of the time histories of regrowth  
515 of stranded wood fragments and associated root resistance is fundamentally important in  
516 the analysis of wood dynamics in rivers. In fact, the statistics of plant growth and force-  
517 displacement parameters are valuable tools for quantitative study of the variation in drag  
518 forces and deterministic prediction of the growth stages of logs when remobilization may  
519 occur. Herein, the evolution of plant biomass was presented in terms of sample averages,  
520 and extrapolated growth laws then fitted to parameters representing below- and above-  
521 ground biomass. In general, the growth trends exhibit power-law behaviour in terms of  
522 root length, number of roots, and average root depth. Due to a lack of studies where de-  
523 structive measurements have been taken, it is hard to deduce whether power fitting curves  
524 can be used to describe the average growth trends of other species and under different  
525 water table conditions. However, for example, based on the experiments of *Imada et al.*  
526 [2008], it has been found that power trends can approximate well the evolution of the root  
527 length of samples of *Populus alba* tested under different water table conditions. It should  
528 be noted that over the duration of the present experiments, root growth tended to be con-  
529 fined, on average, within the unsaturated zone, about 6 cm deep. Given that this depth de-  
530 pends primarily on soil texture, we expect it to be an important factor regarding the extent





506 **Figure 13.** Representation of variations in dimensionless drag force and maximum root resistance with root  
 507 length: a) cutting size  $L=20$  cm and fixed flow velocity  $u$ ; and b) all cutting sizes  $L$  and different values of  $u$ .

531 and growth rate of below-ground biomass. The results have demonstrated that the average  
 532 trends in vegetation growth characteristics are statistically significant. We now consider  
 533 data variability. Low goodness of fit values were obtained from the below-ground biomass  
 534 trends for cuttings of 5 cm length (see Table 2). The variability is due to the intrinsic ran-  
 535 domness of plant development and to heterogeneity of plant characteristics. Even though  
 536 cuttings were collected from the same tree, some did not develop roots, some died, and

537 some sprouted quicker than others even if subjected to the same external conditions (e.g.  
538 sediment, water percentage availability, and stable environment temperature). The variabil-  
539 ity in the data may also be attributed to the limited number of samples when computing  
540 statistical averages. Concerning the above-ground biomass, the logistic law was found to  
541 approximate well the growth trends of the cuttings, until all their nutrient resources had  
542 been depleted. Analysis of the force drops in the force-displacement curves enabled us to  
543 identify statistically the way in which force exerted by and energy stored in the roots are  
544 released under different soil moisture conditions. The present analysis has helped eluci-  
545 date several important features of the uprooting mechanisms that to our knowledge had  
546 remained unexplored to date. In addition, the trend in root surface area along the cuttings  
547 and the link between uprooting force and total root length have revealed promising infor-  
548 mation in terms of upscaling.

549 Several limitations should be considered. First, even though *Salix fragilis* is one of  
550 Europe's largest native willows, the growth characteristics of this species may not be rep-  
551 resentative of all species belonging to *Salicaceae* family. Hence, further investigations are  
552 needed to assess other species characteristics. A second limitation is that the scouring pro-  
553 cesses, accounted in the free-body model of *Bau et al.* [2019], were not considered here.  
554 As a consequence, the type of uprooting simulated here is of Type I. This simplification  
555 is nevertheless consistent with the young growth state of the samples considered. How-  
556 ever, our data interpretation is not yet applicable to more mature vegetation, for which the  
557 scouring around the plant would need to be taken into account, and for which the sedi-  
558 mentary structure and bed morphology around the plant will have evolved. At field scale  
559 and for more mature vegetation, the influence of sediment calibre and the evolution of the  
560 riverbed around the deposited wood (e.g. due to scour processes or fine sediment trap-  
561 ping) still need to be properly tackled. In a more complex scenario, stochastic sources that  
562 are not considered herein (e.g. river processes, the effect of turbulence and flapping mech-  
563 anism) should also be taken into account, given their cumulative contribution to the up-  
564 rooting process [*Perona and Crouzy, 2018*]. Another aspect to consider is the assumption  
565 concerning the impact angle of flow-cutting. When computing the drag force, the cases  
566 solely considered flow impact perpendicular to the longitudinal cross section of the log.  
567 Impacts at other angles were not examined, but warrant future investigation. A further  
568 limitation of the present work is the formulation of the stem length as a total quantity  
569 without considering the number of branches. Such conditions lead to underestimation of

570 the tangential component of the drag force acting on the surface area of vegetation. An-  
571 other constraint arises from having expressed the maximum uprooting force as a function  
572 of total rooting length, which implies that the strength exerted by a long root results from  
573 the summed individual root strength, assuming perfect cooperation among roots [Ennos,  
574 1993]. However, it is quite possible that the pullout force is not built up by individual and  
575 simultaneous contributions of all the roots [Pollen and Simon, 2005; Schwarz *et al.*, 2011;  
576 Pollen-Bankhead and Simon, 2009]. In fact, roots are not pulled in parallel; instead up-  
577 rooting is a slightly cumulative process, as described by Edmaier [2014], whereby a given  
578 root becomes strained just after the loosening of another root previously under tension.  
579 It should nevertheless be noted that the calculation of maximum root resistance included  
580 contributions provided by root hairs and secondary roots, whose cooperation is significant  
581 in multi-root systems [Bailey *et al.*, 2002; Ennos, 1989].

## 582 **6 Conclusions**

583 Vertical pull-out experiments were carried out at the early-stage of growth, in the  
584 context of wood log uprooting, survival, and re-mobilization in rivers during intermit-  
585 tent moderate flooding events. Tests were carried out on root reaction to a vertical pulling  
586 force for plants in soil with different water availability. Sample cuttings of four different  
587 lengths but nearly constant diameter were considered, the aim being to develop upscaling  
588 rules. Force drops in the force-displacement signal were examined to assess how a change  
589 in soil moisture percentage can influence the uprooting process. Fitting laws extrapolated  
590 from the plant growth statistics facilitated computation of an analytical expression of the  
591 drag force and enables definition of the threshold at which a wood log, at a certain stage  
592 of growth, becomes sufficiently resilient to withstand a given hydrologic event. By equat-  
593 ing the flow-induced drag force to maximum root resistance, an expression was derived for  
594 root lengths contributing to the resistant force and, more importantly, time windows when  
595 uprooting may occur. It was found that a certain threshold value of impact flow velocity  
596 had to be reached in order to obtain two distinct uprooting windows. From the analysis,  
597 it was deduced that the modulus of drag force and (accordingly) the flow velocity have to  
598 increase progressively when removing a cutting of increasing size. Despite several limi-  
599 tations (see Discussion), the present analysis provides a useful means by which to inform  
600 new flood protection measures and to understand the contribution of wood logs to river  
601 ecology, management, and restoration. It is hoped that the present experiments will be

602 further reproduced (e.g. for different diameters of cuttings) in order to develop upscaling  
603 rules that would facilitate the derivation of useful allometric laws. The data collected and  
604 analysed as part of the present investigation are freely available to interested parties, the  
605 intention being to support the development of more efficient wood dynamics models that  
606 incorporate biomechanical properties of representative plant species.

607 **A: Nomenclature**

Table A.1: Nomenclature Used in the Paper.

| Symbol            | Description  | Unit                       |
|-------------------|--|----------------------------|
| $A_l$             | total surface area of the foliage                      | [L <sup>2</sup> ]          |
| $A_n$             | drag exposed projected area of the trunk               | [L <sup>2</sup> ]          |
| $A_s$             | total surface area of the stems                        | [L <sup>2</sup> ]          |
| $b$               | logistic growth rate                                   | [T <sup>-1</sup> ]         |
| $C_D$             | drag coefficient                                       | [-]                        |
| $C_f$             | friction coefficient                                   | [-]                        |
| $\bar{d}$         | averaged diameter of the wood log                      | [L]                        |
| $dF$              | force drop height                                      | [M · L · T <sup>-2</sup> ] |
| $d_L$             | major diagonal of the rhombus                          | [L]                        |
| $d_l$             | minor diagonal of the rhombus                          | [L]                        |
| $dt$              | force drop duration                                    | [T]                        |
| $dT$              | force drops intertime                                  | [T]                        |
| $F_{d,n}$         | drag force   | [M · L · T <sup>-2</sup> ] |
| $F_{d,t}$         | friction force   | [M · L · T <sup>-2</sup> ] |
| $\hat{F}_d$       | dimensionless drag force                               | [-]                        |
| $F_n$             | net buoyancy force                                     | [M · L · T <sup>-2</sup> ] |
| $F_{res}$         | last force recovery                                    | [M · L · T <sup>-2</sup> ] |
| $F_{max}$         | maximum uprooting force                                | [M · L · T <sup>-2</sup> ] |
| $L$               | cutting length   | [L]                        |
| $L_r$             | total root length                                      | [L]                        |
| $\bar{L}_r$       | average total root length                              | [L]                        |
| $\bar{L}_s$       | average total stem length                              | [L]                        |
| $\bar{L}_{s,max}$ | averaged total stem length at the maximum growth stage | [L]                        |
| $\bar{l}$         | average root depth                                     | [L]                        |
| $N_{100}^F$       | number of force drops in 100% saturation               | [-]                        |
| $N_{60}^F$        | number of force drops in 60% saturation                | [-]                        |
| $\bar{n}_l$       | averaged number of leaves                              | [-]                        |
| $\bar{n}_r$       | averaged number of roots                               | [-]                        |
| $R$               | maximum root resistance                                | [M · L · T <sup>-2</sup> ] |

Continued on next page

**Table A.1 – continued from previous page**

| Symbol      | Description                              | Unit                                   |
|-------------|--|--|
| $\hat{R}$   | dimensionless maximum root resistance    | [-]                                    |
| $t$         | time                                     | [T]                                    |
| $t_0$       | location of the sigmoid's midpoint       | [T]                                    |
| $u$         | flow velocity impacting the log          | [L· T <sup>-1</sup> ]                  |
| $\bar{V}_r$ | averaged root volume                     | [L <sup>3</sup> ]                      |
| $W$         | uprooting work                           | [M· L <sup>2</sup> · T <sup>-2</sup> ] |
| $\tilde{x}$ | normalised values of the cutting lengths | [-]                                    |
| $\alpha$    | ratio between $dF$ and $dt$              | [M· L· T <sup>-3</sup> ]               |
| $\rho_w$    | water density                            | [M· L <sup>-3</sup> ]                  |
| $\sigma$    | standard deviation                       | [-]                                    |
| $\omega$    | root surface area per unit length        | [L <sup>2</sup> ]                      |

608

609 **Acknowledgments**

610 We want to express our extreme gratitude to Prof Alistair Borthwick for his as-  
611 sistance in revising and editing this manuscript. Acknowledgments are also extended to  
612 Danny-Lee Greiner and Rahul Bharadwaj Prakash for their assistance in carrying out the  
613 experiments. We do not report any conflicts of interest. The dataset used in this manuscript  
614 can be found online on Zenodo (<http://doi.org/10.5281/zenodo.3985848>).

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