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# Biomorphological scaling laws from convectively accelerated streams

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## Abstract

Worldwide convectively accelerated streams flowing into downstream-narrowing river sections show that riverbed vegetation growing on alluvial sediment bars gradually disappears forming a front beyond which vegetation is absent. We revise a recent analytical model able to predict the position of the vegetation front. The model was developed considering the steady state approximation of 1-D eco-morphodynamics equations. While the model was tested against flume experiments, its extension and application to the field is not trivial as it requires the definition of proper scaling laws governing the observed phenomenon. In this work, we present a procedure to calculate vegetation parameters and flow magnitude governing the equilibrium at the reach scale between hydro-morphological and biological components in rivers with converging boundaries. We collected data from worldwide rivers about sections topography, hydro-geomorphological and riparian vegetation characteristics to perform a statistical analysis aimed to validate the proposed procedure. Results are presented in the form of scaling laws correlating biological parameters of growth and decay from different vegetation species to flood return period and duration, respectively. Such relationships demonstrate the existence of underlying selective processes determining the riparian vegetation both in terms of species and cover. We interpret the selection of vegetation species from ecomorphodynamic processes occurring in convectively accelerated streams as the orchestrated dynamical action of flow, sediment and vegetation characteristics.

**Keywords:** fluvial processes; riverbed vegetation; biomass selection; flow uprooting; converging channels

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## 1 Introduction

Riparian and in-channel vegetation must be considered not only as either a source of additional drag to fluvial stream [e.g., *Baptist et al.*, 2007; *Nepf*, 2012; *Vargas-Luna et al.*, 2015, among others] or an agent passively affecting sediment transport and morphological processes [e.g., *Zong and Nepf*, 2010; *Vargas-Luna et al.*, 2016, among others], but also to play an active role within the riverine habitat [*Gurnell*, 2014]. Therefore, it is fundamental to take into account the positive and negative feedbacks between hydro-morpho-dynamics and vegetation establishment, growth and decay [*Edmaier et al.*, 2011; *Perona et al.*, 2012], in order to correctly model river evolution, particularly when referring to long-term predictions. Such mutual interactions gathered attention from scientific community only recently [e.g., see the review by *Camporeale et al.*, 2013]. Specifically, the attention to rivers with converging banks begun with the preliminary conceptual model on island formation proposed by *Gurnell and Petts* [2006] whereas *Edmaier et al.* [2015] and *Bywater-Reyes et al.* [2015] pioneered some studies on the removal conditions of vegetation due to flow in laboratory experiments and field campaigns, respectively. The resulting empirical relationships can be used only when referring to the specific vegetation types involved in their studies. Moreover, results of such predictions are affected by errors mainly originated by the lack of knowledge about the dynamical interactions between vegetation and river morphodynamics [*Solari et al.*, 2016]. Additionally, the temporal and spatial scales at which reciprocal feedbacks between river morphodynamics and riparian vegetation occur still remains an open question [*Manners et al.*, 2015]. Recently developed river eco-morphodynamic models attempt to bridge this gap, by taking into account specific equations for vegetation dynamics (i.e., growth and decay): particularly, the growing term is mainly related to plant-species properties (i.e., by neglecting dependence on nutrient availability and water table level, as usually occurs in river corridors [e.g., *Pasquale et al.*, 2014]), whereas coefficients for decay and mortality due to flow uprooting is intrinsically related to both hydraulic conditions and plant root resistance [*Edmaier et al.*, 2011].

To our knowledge, the first analytical approach to describe eco-morphodynamic interactions has been done by *Perona et al.* [2014], who derived a simple 1-D formulation for the river width where vegetation front is expected to occur in channels with converging banks. Results were validated using previously collected data from laboratory experiments [*Perona et al.*, 2012] but never applied to real case studies. As a matter of fact, in straight channels with parallel riverbanks, vegetation development is mainly imposed on

61 already settled sedimentary emergent patterns, such as bars and islands, [Corenblit *et al.*,  
62 2007; Gurnell, 2014], whereas vegetated rivers with converging boundaries show the dis-  
63 tinguishable pattern of a vegetated area inside the main channel downstream which plants  
64 are likely to be more easily removed (e.g., figure 1 (Replaced: -e,f) replaced with: c-f)).  
65 In this planform configuration, due to the intrinsic and dynamically active flow-biomass  
66 interaction, a distinctive sediment-plant pattern can be commonly found inside the main  
67 channel, particularly, a barebed area where pioneer vegetation is *on average* precluded to  
68 colonize and establish [Perona *et al.*, 2014]. Because of the narrowing longitudinal width,  
69 the stream is convectively forced to accelerate, resulting in increasing velocity and shear  
70 stresses which essentially affect local morphodynamics and promote plant uprooting [Per-  
71 ona *et al.*, 2014], thus limiting the longitudinal establishment and growth of vegetation.  
72 Here we stress the term "*on average*" to highlight that the position of the vegetation front  
73 changes according to flow regime, but its averaged location is set on the long-term pe-  
74 riod (i.e., years). Indeed, such location depends on the inter-time between flood events and  
75 their magnitude. As a matter of fact, vegetation can colonise the area downstream such  
76 position during long low-flow or drought period but it is likely to be uprooted during fol-  
77 lowing high floods, whereas upstream region still remains vegetated. Therefore, vegetation  
78 front is the result of the mutual interactions between plant and river characteristics, which,  
79 at the front, depend on both biological and hydrological time scales.

80 In this work, we studied the interactions between riverbed vegetation and river mor-  
81 phodynamics at the reach scale by following the approach of Perona *et al.* [2014] for rivers  
82 with converging banks. We first validated the formula for the river width where vegetation  
83 front is expected by using already collected data about flow discharge, grain size curve,  
84 sediment transport and riparian vegetation size and growth rate from 35 natural worldwide  
85 rivers (figure 1 (Replaced: -a,b) replaced with: a,b)). Then, we used the validated formula  
86 to calculate the flow discharge return period and the flow decay coefficients characteriz-  
87 ing the vegetation pattern. Lastly, we could correlate biological parameters of growth and  
88 decay to hydrological time scales, and, as a result, prove that vegetation plays a fundamen-  
89 tal role in defining the equilibrium conditions of a river reach according to the different  
90 species.

## 2 Materials and Methods

Most of the river reaches with converging banks show the existence of a specific cross-section beyond which vegetation is on average precluded to establish, i.e., there exists a front where vegetation vanishes. *Perona et al.* [2014] experimentally showed that this results from the intensifying capacity of flow to uproot vegetation due to increasing velocity in the convergent reach. They theoretically derived a formula to calculate the river width where vegetation front is located by taking into account biomass dynamics, the steady state of the system from a one-dimensional approach, the approximation of rectangular cross section, the equation of *Baptist et al.* [2007] for the bed roughness with non-submerged vegetation and a modified version of Meyer-Peter-Müller relation for bedload transport which accounts for the additional critical Shields stress due to the presence of roots [*Pasquale et al.*, 2011]. The proposed equation reads:

$$b_f = c^{3/4} G^{3/8} \left( \theta_c + q_s^{2/3} \right)^{3/8} \left( \frac{\beta}{\phi_m} \right)^{7/8} Q \quad (1)$$

where  $b_f$  is the river width where the vegetation front is located,  $c$  is the Gauckler-Strickler roughness coefficient,  $G = D_{50} \left( \frac{\rho_s}{\rho} - 1 \right)$  is a parameter combining median grain size  $D_{50}$ , sediment density  $\rho_s$  and water density  $\rho$ ,  $\theta_c$  is the critical dimensionless Shield stress for the initiation of sediment movement,  $q_s = \frac{Q_s}{k b}$  is the dimensionless sediment transport per unit width with  $k = 8D_{50}\sqrt{G}g$ ,  $\beta$  is a parameter representing the ratio between vegetation decay rate  $\alpha_d$  and growth rate  $\alpha_g$ ,  $\phi_m$  is the maximum carrying capacity and  $Q$  is the average flow discharge at the steady state. While the critical dimensionless Shield stress for the incipient sediment transport  $\theta_c$  should take into account the presence of plants in the vegetated areas [*Pasquale et al.*, 2011], the value for barebed conditions [e.g., *Chiew and Parker*, 1994] can be assumed when dealing with the area near the vegetation front, where vegetation density is negligible ( $\phi \approx 0$ ). Additionally, it is important to highlight that, while hydraulic coefficients, sediment transport parameters, biomass carrying capacity  $\phi_m$  and growth rate  $\alpha_g$  can be easily calculated or retrieved from literature, the decay rate  $\alpha_d$ , thus  $\beta$ , and the average flow discharge  $Q$  are in general difficult to estimate, and therefore often unknown.

The logistic law for the dynamics of vegetation density  $\phi$  can be expressed as [*Camporeale and Ridolfi*, 2006]:

$$\frac{d\phi}{dt} = \alpha_g \phi (\phi_m - \phi) - \alpha_d \phi Y U^2 \quad (2)$$

122 Therein,  $\alpha_g$  is the growth rate,  $\alpha_d$  is the decay rate due to flow uprooting,  $Y$  is the flow  
 123 depth and  $U$  is the mean flow velocity. We recall that the growth rate  $\alpha_g$  depends on  
 124 species characteristics only (i.e., when water and nutrients are continually available, as  
 125 expected in riverine habitats), whereas the decay rate  $\alpha_d$  is related to both hydraulics and  
 126 vegetation properties [Edmaier et al., 2011].

127 If we assume that growth and decay due to flow are separately active, a possible so-  
 128 lution to the logistic law (Eq. (2)) is given in figure 2. Accordingly, we hypothesise that,  
 129 over a total period  $t_d + t_g$ , the growth and decay terms are active for fractions  $\frac{t_g}{t_d+t_g}$  and  
 130  $\frac{t_d}{t_d+t_g}$ , respectively [Bärenbold et al., 2016; Crouzy et al., 2016]. By accounting for the  
 131 negligible vegetation density at the front (i.e.,  $\phi \ll \phi_m$ ) and the steady state of the solu-  
 132 tion (i.e.,  $\frac{d}{dt} = 0$ ), as hypothesised by Perona et al. [2014], we modify the logistic law and  
 133 obtain:

$$134 \quad \alpha_g \phi_m \frac{t_g}{t_g + t_d} - \alpha_d Y U^2 \frac{t_d}{t_g + t_d} = 0 \quad (3)$$

135 where  $t_g$  is the time for which vegetation grows and  $t_d$  is the time for which vegetation  
 136 is removed due to uprooting. Without entirely reporting the mathematical derivation, for  
 137 which we address the reader to Perona et al. [2014], here below we propose to use Eq. (3)  
 138 in order to rewrite Eq. (1) as

$$139 \quad b_f = c^{3/4} G^{3/8} \left( \theta_c + q_s^{2/3} \right)^{3/8} \left( \frac{\beta}{\phi_m} \right)^{7/8} Q_d \left( \frac{t_d}{t_g} \right)^{7/8} \quad (4)$$

140 where  $Q_d$  is the *reference* flow discharge governing bio-morphological changes at the  
 141 reach scale, a sort of formative discharge controlling vegetation establishment, growth and  
 142 decay. Again, hydro-morphological (i.e., mean grain size and critical Shields number) and  
 143 biological (i.e., carrying capacity and growth rate) parameters can be easily obtained from  
 144 literature or quick field campaigns. On the contrary, quantities related to vegetation de-  
 145 cay (i.e.,  $\alpha_d$ ) and temporal durations (e.g.,  $t_d$  and  $Q$ ) can be obtained by intensive field  
 146 investigations over long monitoring periods only.

147 Here we propose a procedure to calculate the vegetation dynamics parameters and  
 148 overcome the issue. Firstly, we assume that the equilibrium at the reach scale is achieved  
 149 over a yearly time scale, that is  $t_g + t_d = 365$  days. Secondly, as the flood events able  
 150 to uproot vegetation are rare, we expect  $t_d \ll t_g$  (figure 2) and, as a result, it follows  
 151  $t_g \approx 365$  d. By doing so, we assume the disturbances induced by high floods having a  
 152 negligible effect on vegetation growth. Now, by comparing Eq. (1) and Eq. (4) and using

the approximation for  $t_g$ , it is easy to obtain:

$$Q \cdot 365^{7/8} = Q_d \cdot t_d^{7/8} \quad (5)$$

which represents a relation among the flow discharge at the steady state  $Q$ , the *reference* flow discharge  $Q_d$  and the decay duration  $t_d$ . Lastly, the flow duration curve is involved in the system of equations, to have an additional relation between flow discharge and time.

We started our analysis by retrieving data for hydraulic (historical daily mean flow discharge), sediment (grain size curve and sediment transport rate) and riparian vegetation properties (species, cover percentage, age and dimensions) for rivers showing a reach with converging banks. We could collect data for 19 rivers and a total of 35 reaches (figure 1). Although convergent boundaries is a worldwide ubiquitous pattern (see figure 1) and figure 1 in *Perona et al.* [2014]), we selected river reaches according to the availability of previously collected data. For reaches in the same rivers, for which we could not find specific data on sediment transport and vegetation cover, we used information from the near cross section. Data about flow discharge were collected at the closest measuring station and used to calculate the yearly duration curve of daily mean flow discharges, while grain size curve and sediment transport rate were taken from previous studies (see complete references after Table 2). We used the  $D_{50}$  to calculate the coefficient  $G$  and the  $D_{90}$  to calculate the Gauckler-Strickler coefficient  $c$  in Eq. (1). For the riparian vegetation properties, we collected data from previous monitoring studies, particularly concerning species, cover percentage, maturity age and maximum diameter at maturity age (see Table 2 for references about vegetation data). For each river reach, we characterized the vegetation by averaging the parameters of growth rate  $\alpha_g$  and carrying capacity  $\phi_m$  of each species, according to cover percentage, as

$$\bar{\phi}_m = \frac{1}{4046.86} \sum_i \frac{C_i}{b_{0,i}} \left( \frac{D_{max}}{0.0254} \right)^{-b_{1,i}} \quad (6)$$

$$\bar{\alpha}_g = \frac{\pi}{4 \cdot 31536000} \sum_i \frac{C_i D_{max,i}^2}{t_{max,i}} \quad (7)$$

Therein,  $C_i$  is the cover percentage and  $D_{max,i}$  is the diameter at maturity age  $t_{max,i}$  of the  $i$ -th species, being  $b_{0,i}$  and  $b_{1,i}$  two coefficients related to the family of the plant. Eq. (6) was modified from *Arner et al.* [2001] whereas we derived Eq. (7) by considering the growth rate of each single species to be constant during the whole life-stage (i.e., the maturity age  $t_{max,i}$ ). Then, according to similar properties of the predominant vegetation species and cover, the 35 study reaches were gathered in 8 different groups. Table

185 1 summarises group properties and river reach characteristics, whereas all the data can be  
186 found in Table 2. Lastly, we took measurements of river width at the vegetation front from  
187 Google Earth (e.g., figure 1 (Replaced: -e-f) replaced with: c-f)). (Added: Particularly, the  
188 river width was measured along the perpendicular to main flow direction in bankfull con-  
189 ditions.)

191 At this point, we have a system of three equations (i.e., (Replaced: Eqs replaced  
192 with: Equations) (1), (5) and flow duration curve for each river reach) but four unknowns:  
193 the parameter  $\beta = \frac{\alpha_d}{\alpha_g}$ , the *reference* flow discharge  $Q_d$ , the time durations  $t_d$  and the flow  
194 discharge at the steady state  $Q$ . We solve the problem by exploring the space of solutions  
195 in terms of the unknown parameter  $\beta$  over a range of values covering 4 orders of mag-  
196 nitude (i.e., from  $10^0$  to  $10^3 \text{ s}^2 \text{ m}^{-5}$ ) for each river reach in a group. Once fixed a value  
197 of  $\beta$ , the flow discharge at the steady state  $Q$  can be calculated by reversing (Replaced:  
198 Eq. replaced with: Equation) (1). It is now straightforward to calculate the left-hand side  
199 term in (Replaced: Eq. replaced with: Equation) (5). Then, by using the flow duration  
200 curve, it is possible to calculate the  $(t_d, Q_d)$  couples (right-hand side term in (Replaced:  
201 Eq. replaced with: Equation) (5)) that solve the problem. Usually, two pair values appear  
202 as solution (the quantity  $Q_d \cdot t_d^{7/8}$  has a typical parabolic like shape) and, between them,  
203 we select the one with higher  $Q_d$  according to the initial hypothesis  $t_d \ll t_g$ . The proce-  
204 dure is graphically explained in figure 3: the flow duration curve (continuous black line)  
205 is multiplied, once, by the quantity  $365^{7/8}$  (light gray line) to calculate the left-hand side  
206 term and, once, by the corresponding time  $t^{7/8}$  (dashed dark gray line) to obtain the right-  
207 hand side quantity in (Replaced: Eq. replaced with: Equation) (5).

208 Flow discharge  $Q_d$  and the corresponding time  $t_d$  are recorded for all the river reaches  
209 in the same group (i.e., similar vegetation cover) and, then, we calculate the standard devi-  
210 ation of the flow duration  $t_d$ , for each tested value of the parameter  $\beta$ . Figure 4 shows the  
211 clear trend of such standard deviation at varying the parameter  $\beta$  for some groups of river  
212 reaches. As a result, it is possible to identify a minimum in the standard deviation, and,  
213 as we are dealing with equilibrium conditions, a minimum in a function seems to suggest  
214 the presence of scaling laws associated to the predominant vegetation cover. Moreover,  
215 we argue that it is unlikely that different river reaches, with different hydraulic conditions  
216 and morphological characteristics, can satisfy the predicting relation ((Replaced: Eq. re-  
217 placed with: Equation) (1)) and show the existence of such minimum in the  $t_d$  standard  
218 deviation without it being the expression of an underlying fundamental dynamics depend-



**Table 1.** Main vegetation properties and river reaches for each group included in the analysis.

Group	Main properties	Species	Cover	ID	River reaches <sup>a</sup>		
1	Populus ≥ 64%	Balsam poplar	64%	1	Clearwater 1		
		Other willows	33%	2	Clearwater 2		
		Sandbar willow	3%	3	Clearwater 3		
		Douglas fir.	77%	16	Salmon		
		Sandbar willow	23%				
		Plains cottonwood	78%	32	Yellowstone 1		
		Russian olive	16%	33	Yellowstone 2		
		Sandbar willow	6%	34	Yellowstone 3		
					35	Yellowstone 4	
		2	Populus < 55% Tamarix > 30%	Fremont cottonwood	52%		
Salt cedar	41%			14	Rio Grande 1		
Russian olive	6%			15	Rio Grande 2		
Sandbar willow	1%						
Plains cottonwood	42%			17	San Juan 1		
Russian olive	29%						
Salt cedar	29%			18	San Juan 2		
Salt cedar	43%			19	San Juan 3		
Russian olive	36%						
Plains cottonwood	21%						
3	Salix > 30%	Salt cedar	56%	4	Colorado 1		
		Other willows	30%	5	Colorado 2		
		Box elder	14%	6	Colorado 3		
		Goat willow	66%	7	Endrick		
		Common alder	17%				
		Scots pine	17%	8	Feshie		
		Sandbar willow	82%	31	Yampa		
		Box elder	18%				
		4	Eleagnus > 30%	Other willows	60%	11	Little snake 1
				Russian olive	40%	12	Little snake 2
5	Celtis	Netleaf hackberry	100%	23	Snake 1		
					24	Snake 2	
6	Thuja	Western cedar	79%				
		Box elder	13%	13	NF Clearwater		
		Other willows	8%				
		Western cedar	50%				

Group	Main properties	Species	Cover	ID	River reaches <sup>a</sup>
8	Acer, Betula & Picea	Norway spruce	46%		
		Scots pine	31%	10	Kander
		Grey alder	23%		
		Common alder	40%		
		Downy birch	40%	27	Tay
		Scots pine	20%		
		Salt cedar	62%		
		Freemont cottonwood	23%	28	Virgin
		Black willow	15%		
		Water birch	48%	29	Wind 1
		Spruce	36%	30	Wind 2
		Narrowleaf cottonwood	16%		

<sup>a</sup>Numbers, when present, refer to different reaches in the same river

ing on similar vegetation cover. In the end, for a particular vegetation cover (i.e., group  
of river reaches), we select the value of the parameter  $\beta$  corresponding to the minimum  
in the  $t_d$  standard deviation, the calculated *reference* flow discharge  $Q_d$  and its associated  
flow duration  $t_d$ . Lastly, for the river reaches in a group, we calculate an average decay  
rate  $\bar{\alpha}_d = \beta \cdot \bar{\alpha}_g$ .

### 3 Results

We first used the proposed procedure and a dataset of different vegetation cover  
properties and hydro-morphological characteristics to validate the relation derived by *Per-*  
*ona et al.* [2014]. We explored the space of the unknown parameter  $\beta$  (i.e., the ratio be-  
tween decay and growth rates) over four orders of magnitude (i.e., from  $10^0$  to  $10^3 \text{ s}^2 \text{ m}^{-5}$ ,  
see figure 4). As a matter of fact, for higher values of the parameter  $\beta$ , either (~~Replaced:~~  
~~Eq.~~ replaced with: Equation) (1) does not provide any solution or the solution shows very  
high  $t_d$  standard deviation.

As a result, we obtained different values for the parameter  $\beta$  according to the differ-  
ent vegetation properties. We argue that it depends on the interactions among river mor-

234 phology (i.e., river width), river hydrology (i.e., flow duration curve) and, intrinsically,  
235 the characteristic of the vegetation (i.e., species and coverage). We interpret these inter-  
236 actions and the existence of the minimum in the  $t_d$  standard deviation as the orchestrated  
237 dynamical action of flow and morphological adjustments which together contribute to se-  
238 lect vegetation species sharing biomechanics properties that guarantee their survival in  
239 such environments.

240 We used such values of the  $\beta$  parameter to predict the river width at the vegetation  
241 front and compare it against the measured one (e.g., figure 1(Replaced: -e) replaced with:  
242 c)). Figure 5 shows the comparison between measured and calculated river widths at the  
243 vegetation front for each tested river reach. For most of the rivers, the error for the cal-  
244 culated width at the vegetation front is within  $\pm 20\%$  bound, resulting in a high value of  
245 the correlation coefficient ( $R^2 = 0.926$ ). We applied the proposed procedure and the pre-  
246 vious calculated  $\beta$  parameters to two additional rivers not included in Table 1: the Taglia-  
247 mento River (see figure 1(Replaced: -e,f) replaced with: e,f) [Gurnell and Petts, 2006])  
248 and the Maggia River (see Figure 9 in Perona *et al.* [2014]). We found very good agree-  
249 ment between measured and calculated width at the vegetation front for the case study of  
250 the Tagliamento River, whereas the agreement is fairly less good for the Maggia River.  
251 The altered flow regime due to upstream flow regulation, in the case of the Maggia River,  
252 modified the flow duration curve and, as a result, the return period for moderate flood  
253 controlling the vegetation growth and decay is affected when compared to that of natural  
254 flood events. Similar conclusion was given by Perona *et al.* [2014] as well.

255 Furthermore, the procedure proposed in this work allows to calculate the flow mag-  
256 nitude  $Q_d$ , its percentile (namely  $t_d$ ) in the flow duration curve and, additionally, its return  
257 period (i.e.,  $t_d^{-1}$ ). Eventually, (Replaced: Eq. replaced with: Equation) (5) provides the  
258 equivalent steady state flow discharge  $Q$  to be involved in (Replaced: Eq. replaced with:  
259 Equation) (1). We combined such results in scaling relationships both for the averaged  
260 vegetation decay  $\bar{\alpha}_d$  and the averaged growth  $\bar{\alpha}_g$  rates, with respect to the different hydro-  
261 logical time scales. Consequently, we could correlate the first one to the time  $t_d$ , which  
262 fairly resembles the duration of a flood event (figure 6). It is well acknowledged, indeed,  
263 that only during high flood events vegetation can be uprooted and removed, due to the si-  
264 multaneous action of flow drag and bed erosion (Type II uprooting according to Edmaier  
265 *et al.* [2011]). Figure 6 shows that each vegetation cover has a particular combination of  
266 decay rate and temporal scale  $t_d$  governing its removal process. For instance, plant species

267 of Group 2 and 4 (e.g., Tamarix and Eleagnus) are prone to uprooting (i.e., high  $\bar{\alpha}_d$ ) and  
268 can be uprooted with shorter  $t_d$  temporal scale. On the contrary, plants species of Groups  
269 1 and 5 (e.g., Populus and Celtis) resulted stronger against uprooting (i.e., low  $\bar{\alpha}_d$ ) and re-  
270 quire, for instance, deeper bed erosion for their removal during a flood event.

271 As a result, it turns out that instantaneous uprooting (Type I according to *Edmaier*  
272 *et al.* [2011]) is unlikely to occur in riverine habitats with already established vegetation  
273 and certain flood duration is required for morphological changes (i.e., bed erosion) to re-  
274 duce root anchoring and promote plant uprooting [*Perona and Crouzy*, 2018; *Calvani et al.*,  
275 2019].

276 Moreover, we could correlate the average growth rate  $\bar{\alpha}_g$  to the return period of the  
277 flow magnitude  $Q_d$ , which represents a reasonable timescale for plants to start colonising,  
278 establish and grow on river bare bedforms. The flood return period  $T$  was calculated as  
279 the reciprocal of the timescale  $t_d$ : for the sake of clarity,  $T$  is the return period of a daily  
280 flow discharge equal to the *reference* flow discharge  $Q_d$ .

281 The results of the correlation are shown in figure 7. Particularly, figure 7 highlights  
282 that plants with low growth rate (e.g., Group 5 and 7) can survive in fluvial systems char-  
283 acterised by low flow magnitude  $Q_d$  (i.e., short return period  $T$ ). On the contrary, species  
284 with higher growth rate can withstand higher flood events. In this regard, the case of  
285 Tamarix species (Group 2) represents a particular case, as this species is recognised to be  
286 invasive in many ecosystems and, once established, very hard to removed [e.g., *Sher et al.*,  
287 2002; *Stromberg et al.*, 2007]. In such a way, the results suggest that in a given hydro-  
288 morphological fluvial system (i.e., once the channel geometry, grain size distribution and  
289 hydrological regime are fixed), only some plants species, and within the same species,  
290 only mature plants (i.e., old enough to have developed a strong root apparatus) can tackle  
291 flood events. We interpreted these biomorphological scaling relationships as the ability for  
292 rivers to select vegetation according to their growing and survival properties. On the con-  
293 trary, such relationships quantify the ability for plants species to withstand convectively  
294 increasing specific stream power within the converging channel and the particular hydro-  
295 logical conditions.

## 4 Discussion

The role of riparian and in-channel vegetation is commonly acknowledged among the factors controlling the morphodynamic evolution of fluvial environments [see *Campo-reale et al.*, 2013, for a review]. As the presence of such biological component started to be taken into account in modelling only recently [e.g., *van Oorschot et al.*, 2016], the morphodynamic equilibrium at the reach scale is usually modelled by means of empirical relationships, mostly related to bankfull discharge or other characteristic values [e.g., *Parker et al.*, 2007; *Wilkerson and Parker*, 2010], without explicitly accounting for the presence of vegetation. Figure 8 shows the comparison between the measured width at the vegetation front and the predicted bankfull width using the Lacey's relationship [*Savenije*, 2003] for the steady state flow discharge  $Q$  resulting from the performed analysis.

Results are somehow controversial: the bankfull predictor seems to work better in the cases where one can expect vegetation to play a significant role, that is when river width is narrower (i.e., measured  $b_f$  lower than 150 m). On the contrary, for wider rivers, the prediction works well with the proposed formulation (see figure 5 for comparison). This suggests that the steady state flow discharge  $Q$  in ~~(Replaced: Eq. replaced with: Equation)~~ (1) is representative of bankfull discharge only for narrow fluvial systems (i.e., with  $b_f < 150\text{m}$ ), whereas the vegetation dynamics is governed by higher flow discharges in larger rivers. Similarly, vegetation front is located at the bankfull width in small streams, whereas its location is upstream (i.e., where river width is larger due to the convergent configuration) of the bankfull width correspondent to the flow discharge  $Q$ .

Figure 5 shows some predicting errors in the estimation of river width at the vegetation front. Such errors can be ascribed to the simplifications introduced in the model ~~((Replaced: Eq. replaced with: Equation) (4))~~, with particular focus on the one-dimensional approach to river geometry and flow. In this regard, ~~(Replaced: for river reaches showing in-channel vegetated bars (see figure 1(Replaced: -e-f) replaced with: -e-f))~~; replaced with: ~~some river reaches included in the analysis show the presence of large-scale bedforms (i.e., central or multiple bars) covered by in-channel vegetation (see figure 1c-f). For such rivers,~~) it is straightforward to assume the steady state flow discharge  $Q$  as a conceptual value only, whereas the *reference* discharge  $Q_d$  represents the flow governing the vegetation dynamics. Additionally, the evolution of such large-scale bedforms ~~(Deleted: (see figure 1-e,d)-)~~ is not explicitly taken into account in ~~(Replaced: Eq. replaced with: Equa-~~

328 tion) (1) (the model is one-dimensional)(Replaced: ~~but~~ replaced with: . Nevertheless,)  
329 their influence on flow can be considered by an appropriate roughness coefficient  $c$ . Pre-  
330 diction errors can also be correlated to either measuring errors from Google Earth (al-  
331 though limited to some meters) or the different flow period when pictures were taken (e.g.,  
332 low or high water stage). Furthermore, in some cases, due to the absence of measuring  
333 stations, we used similar data of flow duration curve and vegetation cover for different  
334 reaches in the same river, regardless of the distance among them (e.g., reaches 33, 34 and  
335 35 in figure 5). Although we did not identify tributaries from aerial photos, the presence  
336 of small streams may lead to downstream alteration in the flow regime.

337 Analysis results are intrinsically related to the additionally hypothesis made in the  
338 proposed procedure. Conversely to  $t_d$  for  $\bar{\alpha}_d$ , we cannot involved  $t_g$  as a temporal scale  
339 for the growth rate  $\bar{\alpha}_g$ , as we fixed its value ( $t_g \approx 365d$ ). It follows that, according to  
340 the flow regime of each particular river, this approximation may lead to errors when, for  
341 instance, the bio-morphological equilibrium requires longer time to be achieved. Mor-  
342 phodynamic processes (e.g., width adjustment, bank erosion, bar migration) can delay  
343 the achievement of such equilibrium and, in this case, a longer time scale  $t_g$  should be  
344 taken into account. This should also be considered when dealing with important alter-  
345 ations in the flow regime, both in relation to natural changes due to climate change [e.g.,  
346 *Stromberg et al.*, 2010; *Rivaes et al.*, 2013] and human interventions due to flow regulation  
347 [e.g., *Johnson*, 1997] or dam removal [e.g., *Shafroth et al.*, 2002], and in the vegetation  
348 cover, due to alien species colonisation [e.g., *Stromberg et al.*, 2007] or artificial planta-  
349 tions [e.g., *Perry et al.*, 2001]. (Added: It is undisputed that such factors may induced  
350 change in the eco-morphodynamic equilibrium at different temporal scales. A river sub-  
351 jected to flow regulation by damming which, for instance, increases the return period of  
352 the reference flow discharge, will react by showing a narrower  $b_f$  in the short term. In  
353 other words, the vegetation front moves downstream, because, with a higher return period,  
354 plants have longer time to grow and colonise the river bed. However, on the long term,  
355 the new return period will result in a different vegetation cover (selection mechanism),  
356 as pointed out in Figure 7. Similar considerations can be made in the opposite case. )In  
357 this regard, the presence of outliers in figure 6 (Group 6) and in figure 7 (Group 1) can  
358 be explained by considering the main species composing the vegetation cover. Group 1  
359 is mainly constituted by river reaches showing *Populus* species in the plant composition:  
360 poplars are known for its fast growing ( $\bar{\alpha}_g$  in figure 7) and, accordingly, they were artifi-

cially introduced in riverine environments for timber production. Conversely, Group 6 is mainly constituted by reaches showing plants of the genre *Thuja*. Such plants are more typical of swamps and wetlands, rather than riverine habitats, and their low decay rate  $\bar{\alpha}_d$  may be related to the rare occurrence of flow uprooting in such environments [Stewart, 2009].

## 5 Conclusions

In this work, we analysed the interactions between river morphodynamics and vegetation properties at the reach scale. We based our analysis on the one-dimensional equations derived by Perona *et al.* [2014] for the river width where vegetation front is located, provided the existence of an ubiquitous pattern in rivers with convergent boundaries. We first proposed a procedure to calculate the biological parameters and hydrological timescales governing such equilibrium at the reach scale. Accordingly, we validated the proposed procedure against data from real rivers on a yearly time scale, accounting for the effective duration of flow removal, and concluded that vegetation front location is predictable and dependent on the vegetation species, thus providing guidance for future river restoration projects. Due to the defined planform configuration, we could point out the implicit interplays among plants species, river morphology and flow duration. As a result, we demonstrate the ability for rivers to select, by hydrodynamic-induced mortality, biomass (i.e., plant species) according to the flow regime (flood event return period and duration) of the river itself. Furthermore, our analysis shows the importance of accounting for vegetation dynamics and its influence on river properties, both in long-term simulations where flow conditions change in time according to time-scale depending on growth rate  $\alpha_g$  and at the flood event scale, where vegetation density changes according to  $\alpha_d$ : therefore, the choice of time-scale and time-step shall reflect not only hydraulic conditions but also vegetation properties.

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## References

- Al-Ansari, N., and J. McManus (1979), Fluvial sediments entering the tay estuary: sediment discharge from the river earn, *Scottish Journal of Geology*, 15(3), 203–216.
- Andrews, E. D. (1980), Effective and bankfull discharges of streams in the yampa river basin, colorado and wyoming, *Journal of Hydrology*, 46(3-4), 311–330.
- Andrews, E. D. (1984), Bed-material entrainment and hydraulic geometry of gravel-bed rivers in colorado, *Geological Society of America Bulletin*, 95(3), 371–378.
- Arner, S. L., S. Woudenberg, S. Waters, J. Vissage, C. MacLean, M. Thompson, and M. Hansen (2001), National algorithms for determining stocking class, stand size class, and forest type for forest inventory and analysis plots, *Internal Rep. Newtown Square, PA: US Department of Agriculture, Forest Service, Northeastern Research Station*. 10p.
- Ashworth, P. J., and R. I. Ferguson (1989), Size-selective entrainment of bed load in gravel bed streams, *Water Resources Research*, 25(4), 627–634.
- Auble, G. T., J. M. Friedman, P. B. Shafroth, M. F. Merigliano, and M. L. Scott (2012), Woody riparian vegetation near selected streamgages in the western united states, *US Geological Survey Data Series, Data series: 708*.
- BAFU Data (2017), erhebung von Daten zum Umweltzustand des Bundesamtes für Umwelt; <https://www.bafu.admin.ch/bafu/de/home/zustand/daten/umweltdaten.html>.
- BAFU GeoData (2017), verfügbare Geodaten des Bundesamtes für Umwelt; <https://www.bafu.admin.ch/bafu/de/home/zustand/daten/geodaten.html>.
- Baptist, M., V. Babovic, J. Rodríguez Uthurburu, M. Keijzer, R. Uittenbogaard, A. Mynett, and A. Verwey (2007), On inducing equations for vegetation resistance, *Journal of Hydraulic Research*, 45(4), 435–450.
- Bärenbold, F., B. Crouzy, and P. Perona (2016), Stability analysis of ecomorphodynamic equations, *Water Resources Research*, 52(2), 1070–1088.
- Bates, C., C. Moore, T. Malthus, J. Mair, and E. Karpouzli (2004), Broad scale mapping of habitats in the firth of tay and eden estuary, scotland, *Scottish Natural Heritage Comissioned Report*, 7.
- Bryant, R. G., and D. J. Gilvear (1999), Quantifying geomorphic and riparian land cover changes either side of a large flood event using airborne remote sensing: River tay, scotland, *Geomorphology*, 29(3-4), 307–321.



- 421 Bywater-Reyes, S., A. C. Wilcox, J. C. Stella, and A. F. Lightbody (2015), Flow and scour  
422 constraints on uprooting of pioneer woody seedlings, *Water Resources Research*, 51(11),  
423 9190–9206.
- 424 Calvani, G., S. Francalanci, and L. Solari (2019), A physical model for the uprooting  
425 of flexible vegetation on river bars, *Journal of Geophysical Research: Earth Surface*,  
426 124(4), 1018–1034, doi:10.1029/2018JF004747.
- 427 Camporeale, C., and L. Ridolfi (2006), Riparian vegetation distribution induced by river  
428 flow variability: A stochastic approach, *Water Resources Research*, 42(10).
- 429 Camporeale, C., E. Perucca, L. Ridolfi, and A. Gurnell (2013), Modeling the interactions  
430 between river morphodynamics and riparian vegetation, *Reviews of Geophysics*, 51(3),  
431 379–414.
- 432 Charlton, F., P. Brown, and R. Benson (1978), *The hydraulic geometry of some gravel*  
433 *ivers in Britain*, Hydraulics Research Station, Wallingford (UK).
- 434 Chiew, Y.-M., and G. Parker (1994), Incipient sediment motion on non-horizontal slopes,  
435 *Journal of Hydraulic Research*, 32(5), 649–660.
- 436 Claessens, H., A. Oosterbaan, P. Savill, and J. Rondeux (2010), A review of the character-  
437 istics of black alder (*Alnus glutinosa* (L.) Gaertn.) and their implications for silvicultural  
438 practices, *Forestry*, 83(2), 163–175.
- 439 Corenblit, D., E. Tabacchi, J. Steiger, and A. M. Gurnell (2007), Reciprocal interactions  
440 and adjustments between fluvial landforms and vegetation dynamics in river corridors: a  
441 review of complementary approaches, *Earth-Science Reviews*, 84(1), 56–86.
- 442 Crouzy, B., F. Bärenbold, P. D'Ágostino, and P. Perona (2016), Ecomorphodynamic  
443 approaches to river anabranching patterns, *Advances in water resources*, 93, 156–165.
- 444 Edmaier, K., P. Burlando, and P. Perona (2011), Mechanisms of vegetation uprooting by  
445 flow in alluvial non-cohesive sediment, *Hydrology and Earth System Sciences*, 15(5),  
446 1615–1627.
- 447 Edmaier, K., B. Crouzy, and P. Perona (2015), Experimental characterization of vegeta-  
448 tion uprooting by flow, *Journal of Geophysical Research: Biogeosciences*, 120(9), 1812–  
449 1824.
- 450 Elliott, J. G., and S. P. Anders (2004), *Summary of sediment data from the Yampa River*  
451 *and Upper Green River basins, Colorado and Utah, 1993-2002*, 5242, US Department of  
452 the Interior, US Geological Survey.

453 Enescu, C., T. H. Durrant, D. de Rigo, and G. Caudullo (2016), *Salix caprea* in europe:  
454 distribution, habitat, usage and threats, in *European atlas of forest tree species*, Publica-  
455 tions Office of the European Union, Luxembourg (L).

456 FLO Engineering, I. (1994), Little snake river channel monitoring project, *Tech. Rep. 1994*  
457 *fall channel monitoring trip*, US Fish and Wildlife Service, National Park Service and  
458 Colorado State University.

459 Gilvear, D., J. Cecil, and H. Parsons (2000), Channel change and vegetation diversity on a  
460 low-angle alluvial fan, river feshie, scotland, *Aquatic Conservation: Marine and Fresh-*  
461 *water Ecosystems*, 10(1), 53–71.

462 Gurnell, A. (2014), Plants as river system engineers, *Earth Surface Processes and Land-*  
463 *forms*, 39(1), 4–25.

464 Gurnell, A., and G. Petts (2006), Trees as riparian engineers: the Tagliamento River, Italy,  
465 *Earth Surface Processes and Landforms*, 31(12), 1558–1574.

466 Heins, A., A. Simon, L. Farrugia, and M. Findeisen (2004), Bed-material characteristics of  
467 the san juan river and selected tributaries, new mexico: developing protocols for stream-  
468 bottom deposits, *Tech. Rep. No. 47*, USDA-ARS.

469 Hoag, J. C. (2005), Simple identification key to common willows, cottonwoods, alder,  
470 birch and dogwood of the intermountain west, *Aberdeen (ID): USDA Natural Resources*  
471 *Conservation Service, Aberdeen Plant Materials Center. Riparian/Wetland Project Infor-*  
472 *mation Series*, 19, 16.

473 Holnbeck, S. R. (2005), *Sediment-transport investigations of the Upper Yellowstone River,*  
474 *Montana, 1999 through 2001: data collection, analysis, and simulation of sediment trans-*  
475 *port*, US Department of the Interior, US Geological Survey.

476 Johnson, W. C. (1997), Equilibrium response of riparian vegetation to flow regulation in  
477 the platte river, nebraska, *Regulated Rivers: Research & Management: An International*  
478 *Journal Devoted to River Research and Management*, 13(5), 403–415.

479 Jud, D. (2009), Eigendynamische flussaufweitungen der kander im gebiet heustrich süd,  
480 masters' thesis, EPFL, Losanne (CH).

481 Little, E. L., and L. A. Viereck (1971), *Atlas of United States trees*, vol. 5, US Dept. of  
482 Agriculture, Forest Service, Washington, DC.

483 Manners, R. B., A. C. Wilcox, L. Kui, A. F. Lightbody, J. C. Stella, and L. S. Sklar  
484 (2015), When do plants modify fluvial processes? Plant-hydraulic interactions under  
485 variable flow and sediment supply rates, *Journal of Geophysical Research: Earth Sur-*

486 *face*, 120(2), 325–345.

487 Mueller, E. R., and J. Pitlick (2013), Sediment supply and channel morphology in moun-  
488 tain river systems: 1. relative importance of lithology, topography, and climate, *Journal*  
489 *of Geophysical Research: Earth Surface*, 118(4), 2325–2342.

490 Mueller, E. R., J. Pitlick, and J. M. Nelson (2005), Variation in the reference shields stress  
491 for bed load transport in gravel-bed streams and rivers, *Water Resources Research*,  
492 41(4).

493 National River Flow Archive (2017), <https://nrfa.ceh.ac.uk/>.

494 Nepf, H. M. (2012), Hydrodynamics of vegetated channels, *Journal of Hydraulic Research*,  
495 50(3), 262–279.

496 Novak, S. J. (2006), Hydraulic modelling analysis of the middle rio grande river from co-  
497 chiti dam to galisteo creek, new mexico, masters' thesis, Colorado State University, Fort  
498 Collins, CO (USA).

499 Parker, G., P. R. Wilcock, C. Paola, W. E. Dietrich, and J. Pitlick (2007), Physical basis  
500 for quasi-universal relations describing bankfull hydraulic geometry of single-thread  
501 gravel bed rivers, *Journal of Geophysical Research: Earth Surface*, 112(F4).

502 Pasquale, N., P. Perona, P. Schneider, J. Shrestha, A. Wombacher, and P. Burlando (2011),  
503 Modern comprehensive approach to monitor the morphodynamic evolution of a restored  
504 river corridor, *Hydrology and Earth System Sciences*, 15(4), 1197–1212.

505 Pasquale, N., P. Perona, R. Francis, and P. Burlando (2014), Above-ground and below-  
506 ground Salix dynamics in response to river processes, *Hydrological processes*, 28(20),  
507 5189–5203.

508 Perona, P., and B. Crouzy (2018), Resilience of riverbed vegetation to uprooting by flow,  
509 *Proc. R. Soc. A*, 474(2211).

510 Perona, P., P. Molnar, B. Crouzy, E. Perucca, Z. Jiang, S. McLelland, D. Wüthrich, K. Ed-  
511 maier, R. Francis, C. Camporeale, et al. (2012), Biomass selection by floods and related  
512 timescales: Part 1. experimental observations, *Advances in Water Resources*, 39, 85–96.

513 Perona, P., B. Crouzy, S. McLelland, P. Molnar, and C. Camporeale (2014), Ecomorpho-  
514 dynamics of rivers with converging boundaries, *Earth Surface Processes and Landforms*,  
515 39(12), 1651–1662.

516 Perry, C. H., R. C. Miller, and K. N. Brooks (2001), Impacts of short-rotation hybrid  
517 poplar plantations on regional water yield, *Forest Ecology and Management*, 143(1-3),  
518 143–151.

519 Piedra, M. M. (2010), Flume investigation of the effects of sub-threshold rising flows on  
520 the entrainment of gravel beds, Ph.D. thesis, University of Glasgow, Glasgow (UK).

521 Rivaes, R., P. M. Rodríguez-González, A. Albuquerque, A. N. Pinheiro, G. Egger, and  
522 M. T. Ferreira (2013), Riparian vegetation responses to altered flow regimes driven by  
523 climate change in mediterranean rivers, *Ecohydrology*, 6(3), 413–424.

524 Savenije, H. H. (2003), The width of a bankfull channel; lacey’s formula explained, *Jour-*  
525 *nal of Hydrology*, 276(1-4), 176–183.

526 Shafroth, P. B., J. M. Friedman, G. T. Auble, M. L. Scott, and J. H. Braatne (2002), Po-  
527 tential responses of riparian vegetation to dam removal: dam removal generally causes  
528 changes to aspects of the physical environment that influence the establishment and  
529 growth of riparian vegetation, *BioScience*, 52(8), 703–712.

530 Sharma, M., and J. Parton (2007), Height–diameter equations for boreal tree species in on-  
531 tario using a mixed-effects modeling approach, *Forest Ecology and Management*, 249(3),  
532 187–198.

533 Sher, A. A., D. L. Marshall, and J. P. Taylor (2002), Establishment patterns of native pop-  
534 ulus and salix in the presence of invasive nonnative tamarix, *Ecological applications*,  
535 12(3), 760–772.

536 Smith, H. Y. (1999), Assessing longevity of ponderosa pine (*pinus ponderosa*) snags in  
537 relation to age, diameter, wood density and pitch content, masters’ thesis, University of  
538 Montana, Missoula, MT (USA).

539 Solari, L., M. Van Oorschot, B. Belletti, D. Hendriks, M. Rinaldi, and A. Vargas-Luna  
540 (2016), Advances on modelling riparian vegetation-hydromorphology interactions, *River*  
541 *Research and Applications*, 32(2), 164–178.

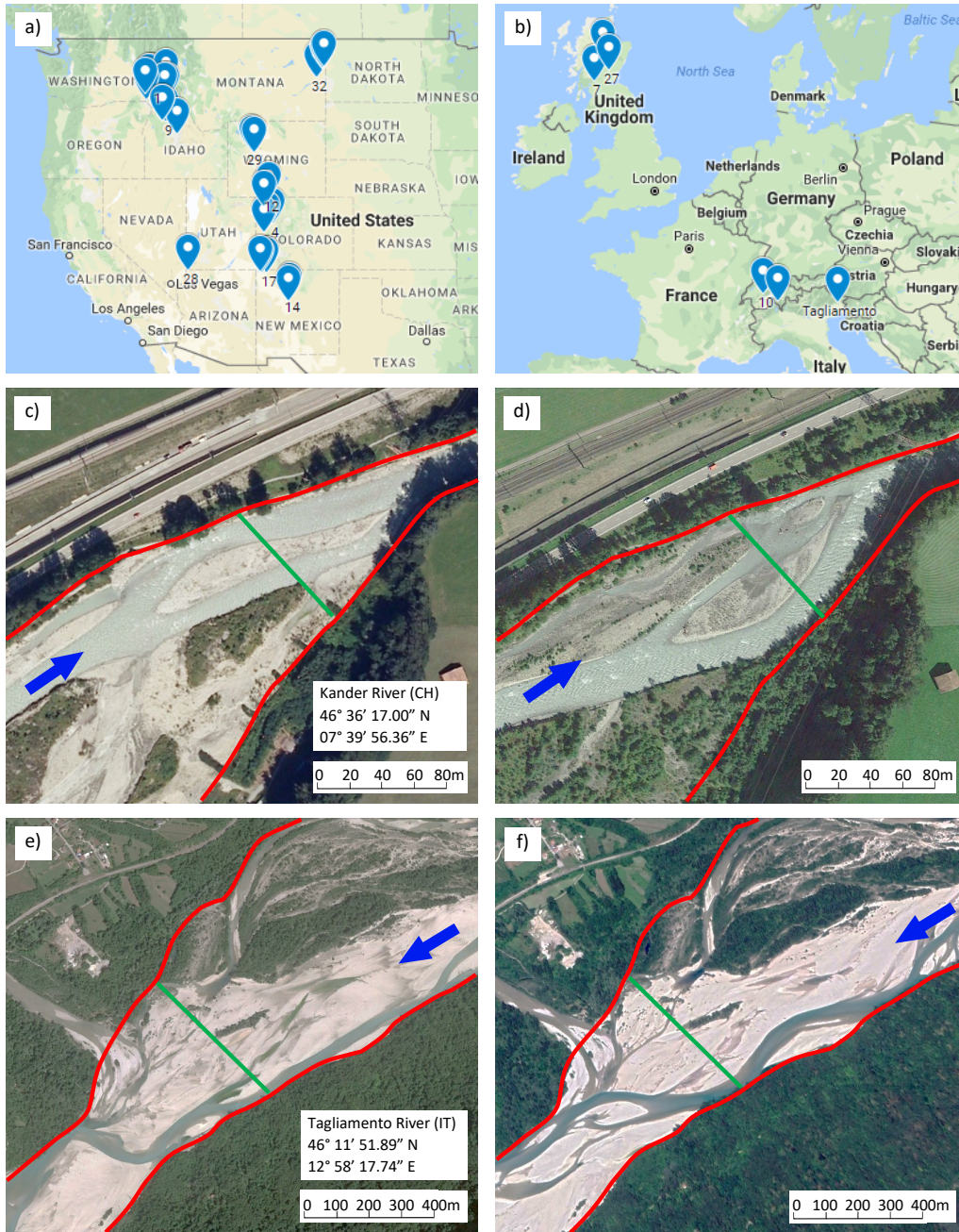
542 Stewart, H. (2009), *Cedar: tree of life to the Northwest Coast Indians*, D & M Publishers.

543 Stromberg, J. C., S. J. Lite, R. Marler, C. Paradzick, P. B. Shafroth, D. Shorrock, J. M.  
544 White, and M. S. White (2007), Altered stream-flow regimes and invasive plant species:  
545 the tamarix case, *Global Ecology and Biogeography*, 16(3), 381–393.

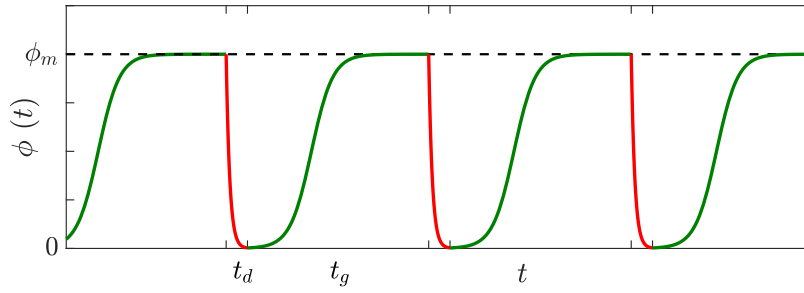
546 Stromberg, J. C., S. J. Lite, and M. Dixon (2010), Effects of stream flow patterns on ripar-  
547 ian vegetation of a semiarid river: implications for a changing climate, *River Research*  
548 *and Applications*, 26(6), 712–729.

549 van Oorschot, M., M. Kleinhans, G. Geerling, and H. Middelkoop (2016), Distinct pat-  
550 terns of interaction between vegetation and morphodynamics, *Earth Surface Processes*  
551 *and Landforms*, 41(6), 791–808.

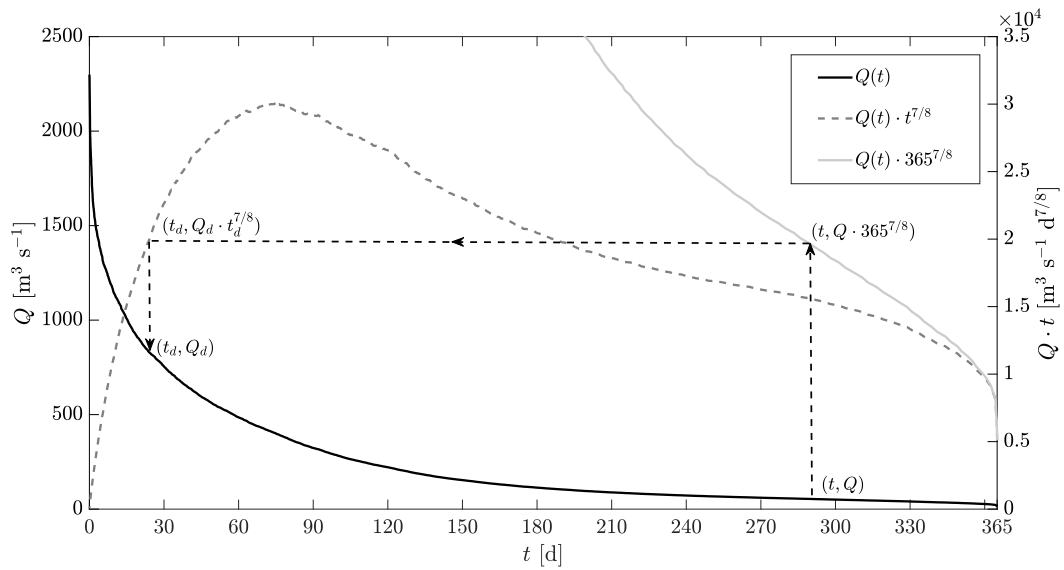
- 552 Vargas-Luna, A., A. Crosato, and W. S. Uijttewaal (2015), Effects of vegetation on flow  
553 and sediment transport: comparative analyses and validation of predicting models, *Earth*  
554 *Surface Processes and Landforms*, 40(2), 157–176.
- 555 Vargas-Luna, A., A. Crosato, G. Calvani, and W. S. Uijttewaal (2016), Representing plants  
556 as rigid cylinders in experiments and models, *Advances in Water Resources*, 93, 205–  
557 222.
- 558 Warner, R., and K. Hendrix (1984), *California riparian systems: ecology, conservation,*  
559 *and productive management*, University of California Press, Berkeley, CA (USA).
- 560 Water Data for the Nation (2017), <https://waterdata.usgs.gov/nwis>.
- 561 Wilkerson, G. V., and G. Parker (2010), Physical basis for quasi-universal relationships  
562 describing bankfull hydraulic geometry of sand-bed rivers, *Journal of Hydraulic Engi-*  
563 *neering*, 137(7), 739–753.
- 564 Zong, L., and H. Nepf (2010), Flow and deposition in and around a finite patch of vegeta-  
565 tion, *Geomorphology*, 116(3), 363–372.



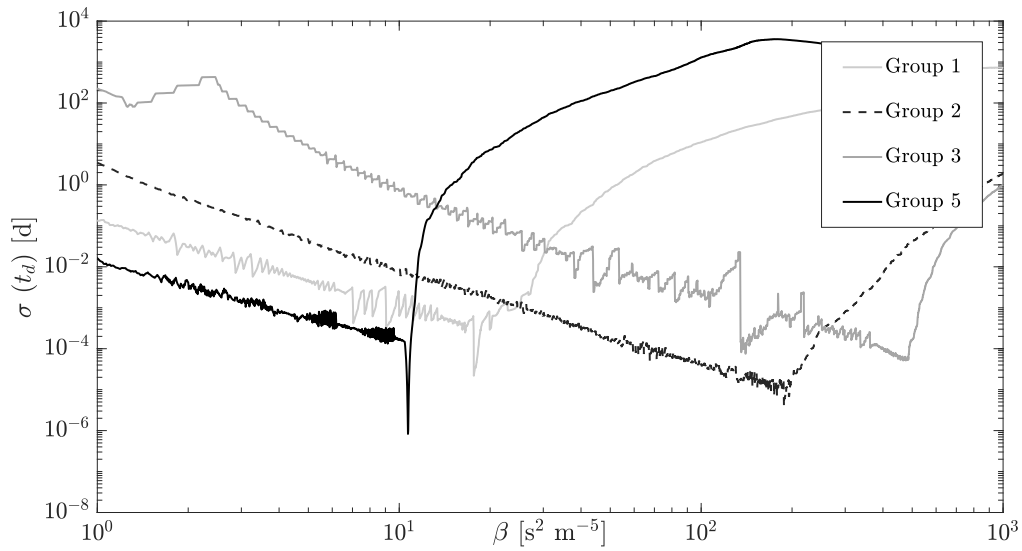
566 **Figure 1.** Convergent banks in rivers are an ubiquitous planform configuration. a,b) Worldwide location  
 567 of the river reaches included in the analysis - Images from Google Earth. c) A reach of the Kander River  
 568 (Switzerland) showing the presence of a vegetation front in 2009. d) The same reach of the Kander River  
 569 in 2016. Although bar morphology changed, the location of the vegetation front is stable. e) A reach of the  
 570 Tagliamento River (Italy) showing the presence of a vegetation front in 2016. f) The same reach of the Taglia-  
 571 mento River in 2018, with unchanged position of the vegetation front. Red lines highlight the converging  
 572 configuration of riverbanks. Green lines show the position of the vegetation front.



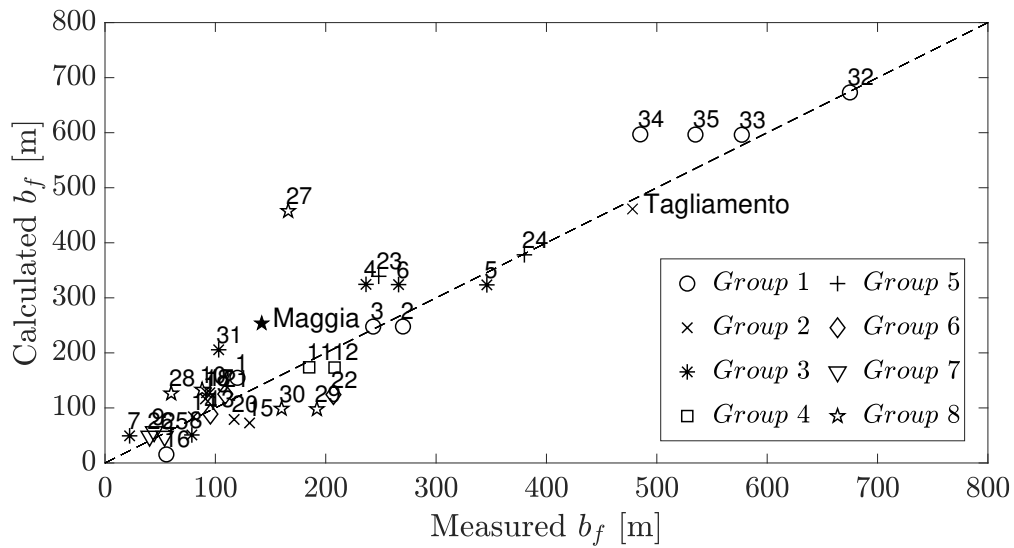
573 **Figure 2.** A possible solution to the logistic law for vegetation dynamics ((Replaced: Eq. replaced with:  
 574 Equation) (2)) when growth and decay terms are separately active. Green line represents the solution consid-  
 575 ering the growing term governed by  $\alpha_g$  and  $t_g$  is its duration. Red line is the solution considering the decay  
 576 rate  $\alpha_d$  only and  $t_d$  is the decay duration.



577 **Figure 3.** A common flow duration curve (continuous black line) and the associated parabolic-like shape  
 578 curve obtained as a result of the product by its duration time to the power of 7/8 (dashed dark-gray line).  
 579 Continuous light-gray curve is the flow duration curve multiplied by  $365^{7/8}$ . Dashed black lines show the  
 580 calculation of the flow discharge  $Q_d$  and its relative duration time  $t_d$ .

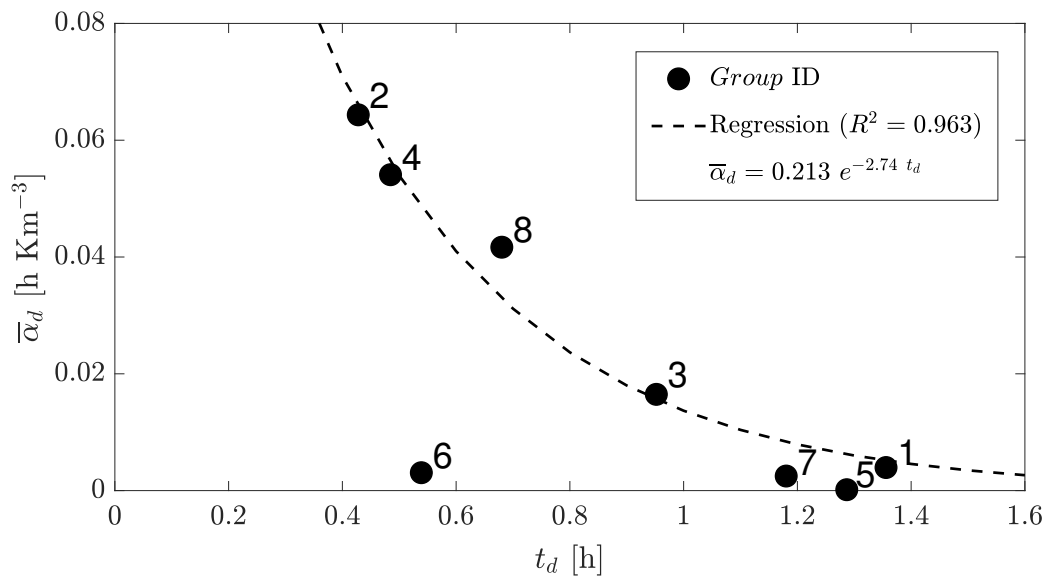


581 **Figure 4.**  $t_d$  standard deviation ( $\sigma$ ) versus the parameter  $\beta$  at varying the vegetation cover properties (i.e.,  
 582 river group). The curves show the  $t_d$  standard deviation slowly decreasing and fast rising after having reached  
 583 a minimum.

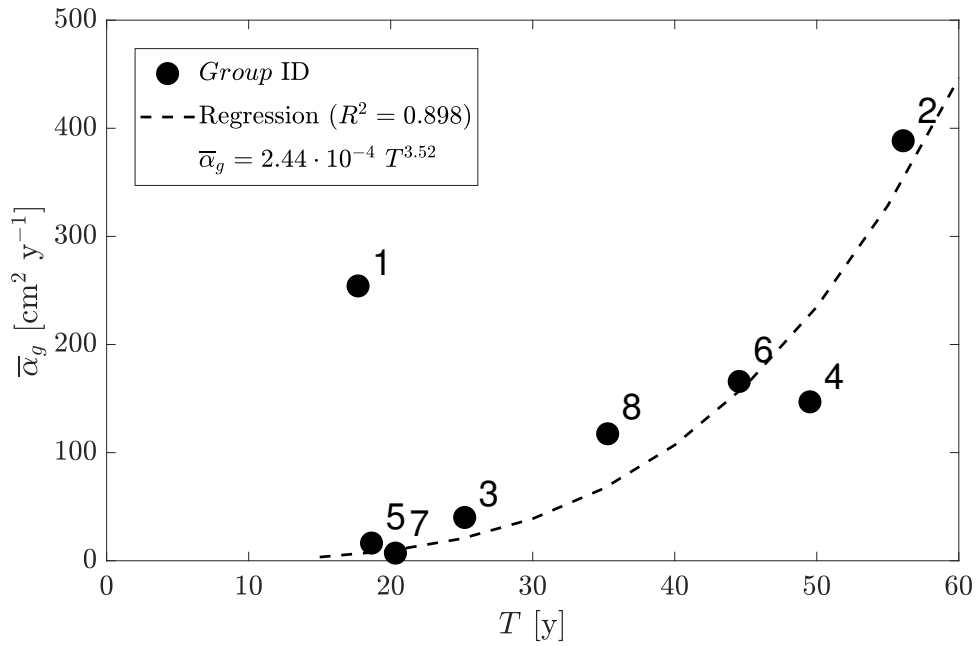


584 **Figure 5.** Comparison between measured and calculated river width at the vegetation front ( $b_f$ ) for the  
 585 river reaches we tested, according to different vegetation cover (Group ID). The comparison for the Maggia  
 586 River (Group 8 - black star) and the Tagliamento River (Group 2 - black cross) is shown as validation cases.

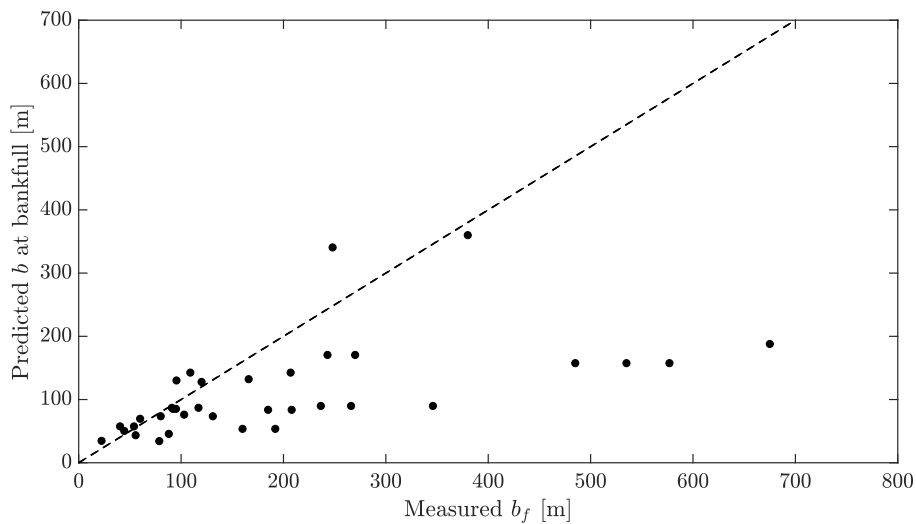




587 **Figure 6.** Average vegetation decay coefficient  $\bar{\alpha}_d$  versus the characteristics time  $t_d$  in the flow duration  
 588 curve controlling the biomorphological properties at the reach scale. Each vegetation cover is characterised  
 589 by a particular combination of decay rate  $\bar{\alpha}_d$  and temporal scale in the flow duration curve, showing that  
 590 underlying interactions between hydro-morphology and vegetation govern the uprooting process at the reach  
 591 scale, according to the different plant species.



592 **Figure 7.** Average vegetation growth rate  $\bar{\alpha}_g$  versus the return period  $T$  of the flow controlling the river  
 593 width at the reach scale. Species with higher growth rate can develop a strong root apparatus so withstand and  
 594 survive to higher flow discharges. Conversely, slowly growing plants are more susceptible to be uprooted even  
 595 for low flow events.



596 **Figure 8.** Comparison between measured width at the vegetation front and the bankfull width predicted  
 597 using Lacey's relation for the steady flow discharge  $Q$ . Agreement is good only for very small rivers whereas  
 598 it is lost for widths larger than approximately 150m.

		[° ' ''	[° ' ''	[m]	[%o]	[mm]	[mm]	[m <sup>3</sup> d <sup>-1</sup> ]	Species	Cover [%]	[cm <sup>2</sup> y <sup>-1</sup> ]	[10 <sup>-3</sup> m <sup>-2</sup> ]
1	Clearwater 1 (5)(17)(21)(22)(26)(28)(29)	46° 29'	116° 15'	120	1.57	58.8	114.2	200.7	Balsam poplar	64%	79.94	35.46
		17.01'' N	41.91'' W						Other willows	33%		
									Sandbar willow	3%		
2	Clearwater 2 (5)(17)(21)(22)(26)(28)(29)	46° 31'	116° 40'	270	1.29	44.4	111.3	200.7	Balsam poplar	64%	79.94	35.46
		16.97'' N	08.12'' W						Other willows	33%		
									Sandbar willow	3%		
3	Clearwater 3 (5)(17)(21)(22)(26)(28)(29)	46° 29'	116° 44'	243	1.29	44.4	111.3	200.7	Balsam poplar	64%	79.94	35.46
		19.63'' N	28.74'' W						Other willows	33%		
									Sandbar willow	3%		
16	Salmon (5)(20)(21)(22)(28)(29)	44° 15'	114° 41'	56	3.40	104	396	12.96	Douglas fir.	77%	309.6	44.14
		14.13'' N	00.59'' W						Sandbar willow	23%		
32	Yellowstone 1 (5)(17)(18)(21)(22)(28)(29)	47° 07'	104° 42'	675	0.75	57	160	1382	Plains cotton.	79%	369.3	15.17
		42.86'' N	05.16'' W						Russian olive	15%		
									Sandbar willow	6%		
33	Yellowstone 2 (5)(17)(18)(21)(22)(28)(29)	47° 30'	104° 15'	577	0.36	57	160	1382	Plains cotton.	78%	375.6	11.56
		14.49'' N	22.42'' W						Russian olive	14%		
									Peach. willow	5%		
34	Yellowstone 3 (5)(17)(18)(21)(22)(28)(29)	47° 35'	104° 12'	485	0.36	57	160	1382	Plains cotton.	78%	375.6	11.56
		27.12'' N	36.41'' W						Russian olive	14%		
									Peach. willow	5%		
35	Yellowstone 4 (5)(17)(18)(21)(22)(28)(29)	47° 37'	104° 10'	535	0.36	57	160	1382	Plains cotton.	78%	375.6	11.56
		36.64'' N	07.75'' W						Russian olive	14%		
									Peach. willow	5%		
								Sandbar willow	3%			

Group ID	Site <sup>a</sup> (Ref.)	Latitude		Longitude		$B_f$ [m]	$S$ [%c]	$D_{50}$ [mm]	$D_{90}$ [mm]	$Q_s$ [ $m^3 d^{-1}$ ]	Vegetation characteristics and parameters		
		[° , '"]	[° , '"]	[° , '"]	[° , '"]						Species	Cover [%]	$\bar{\alpha}_g$ [ $cm^2 y^{-1}$ ]
14	Rio Grande 1 (5)(10)(17)(22)(24)(28)(29)	35° 16'	106° 35'	80	0.83	0.462	1.125	2247	Fremont cotton.	52%			
		13.96'' N	35.41'' W						Salt cedar	41%	1.4090	63.56	
										Russian olive	6%		
										Sandbar willow	1%		
15	Rio Grande 2 (5)(10)(17)(22)(24)(28)(29)	35° 05'	106° 41'	131	0.83	0.462	1.125	2247	Fremont cotton.	52%			
		53.99'' N	35.28'' W						Salt cedar	41%	444.3	63.56	
										Russian olive	6%		
										Sandbar willow	1%		
17	San Juan 1 (5)(10)(16)(17)(22)(28)	36° 43'	108° 14'	95	4.10	40	100	28.51	Plains cotton.	42%			
		57.83'' N	58.31'' W						Russian olive	29%	1.362	50.00	
										Salt cedar	29%		
										Plains cotton.	42%		
18	San Juan 2 (5)(10)(16)(17)(22)(28)	36° 43'	108° 18'	92	4.10	40	100	28.51	Plains cotton.	42%			
		23.14'' N	53.63'' W						Russian olive	29%	429.5	50.00	
										Salt cedar	29%		
										Plains cotton.	42%		
19	San Juan 3 (5)(10)(16)(17)(22)(28)	36° 46'	108° 39'	91	1.45	90	240	28.51	Salt cedar	43%			
		22.16'' N	28.03'' W						Russian olive	36%	291.7	72.59	
										Plains cotton.	21%		
										Salt cedar	43%		
20	San Juan 4 (5)(10)(16)(17)(22)(28)	36° 47'	108° 41'	117	1.45	90	240	28.51	Salt cedar	43%			
		12.68'' N	38.69'' W						Russian olive	36%	291.7	72.59	
										Plains cotton.	21%		
										Salt cedar	43%		

<sup>a</sup>Numbers, when present, refer to different reaches in the same river.

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Group	(Ref.)	[° ' '']	[° ' '']	[m]	[‰]	[mm]	[mm]	[m <sup>3</sup> d <sup>-1</sup> ]	Species	Cover	$\bar{\alpha}_g$	$\bar{\phi}_m$
										[%]	[cm <sup>2</sup> y <sup>-1</sup> ]	[10 <sup>-3</sup> m <sup>-2</sup> ]
4	Colorado 1 (17)(20)(22)(28)(29)	39° 30'	107° 50'	237	2.71	58	90	247.5	Salt cedar	56%	38.47	129.3
		59.02'' N	27.87'' W						Other willows	30%		
									Box elder	14%		
5	Colorado 2 (17)(20)(22)(28)(29)	39° 18'	108° 13'	346	2.71	58	90	247.5	Salt cedar	56%	38.47	129.3
		40.61'' N	30.36'' W						Other willows	30%		
									Box elder	14%		
6	Colorado 3 (17)(20)(22)(28)(29)	39° 03'	108° 26'	266	2.71	58	90	247.5	Salt cedar	56%	38.47	129.3
		35.67'' N	36.66'' W						Other willows	30%		
									Box elder	14%		
7	Endrik (11)(13)(15)(23)(25)	56° 03'	004° 27'	22	1.44	28.9	57.3	524.1	Goat willow	66%	43.84	114.3
		19.78'' N	10.80'' W						Common alder	17%		
									Scots pine	17%		
8	Feshie (4)(11)(13)(15)(23)	57° 05'	003° 54'	79	9.62	54	90	20.82	Goat willow	66%	43.84	114.3
		32.40'' N	11.34'' W						Common alder	17%		
									Scots pine	17%		
31	Yampa (2)(3)(5)(12)(22)(28)	40° 27'	108° 25'	103	1.26	34	82	359.1	Sandbar willow	82%	37.53	124.2
		40.54'' N	29.27'' W						Box elder	18%		
11	Little Snake 1 (2)(5)(14)(17)(22)(28)	40° 35'	108° 23'	185	1.23	48.5	87.0	857.5	Other willows	60%	147.0	97.40
		16.76'' N	02.08'' W						Russian olive	40%		
12	Little Snake 2 (2)(5)(14)(17)(22)(28)	40° 53'	108° 07'	208	1.23	48.5	87.0	857.5	Other willows	60%	147.0	97.40
		06.27'' N	29.89'' W						Russian olive	40%		
23	Snake 1 (5)(20)(21)(22)(28)	46° 02'	116° 55'	248	1.16	54.0	90.0	172.8	Netl. hackberry	100%	163.7	77.33
		21.87'' N	48.00'' W									
24	Snake 2 (5)(20)(21)(22)(28)	46° 18'	117° 00'	380	0.47	54.0	90.0	172.8	Netl. hackberry	100%	163.7	77.33
		26.35'' N	28.75'' W									

**Table 2.** Summary of collected data for the 35 river cross-sections. Group refers to similar characteristics of vegetation cover.

Group	ID	Site <sup>a</sup> (Ref.)	Latitude		Longitude		$B_f$ [m]	$S$ [‰]	$D_{50}$ [mm]	$D_{90}$ [mm]	$Q_s$ [ $m^3 d^{-1}$ ]	Vegetation characteristics and parameters		
			[° , '"]	[° , '"]	[° , '"]	[° , '"]						Species	Cover [%]	$\bar{\alpha}_g$ [ $cm^2 y^{-1}$ ]
6	13	NF Clearwater (6)(7)(10)(19)(22)	46° 45'	115° 31'	96	7.94	95	282	26.87	Western cedar	79%	163.7	35.11	
			04.96" N	12.53" W	109	2.60	24	131	70.50	Box elder	13%			
											Other willows	8%		
6	21	Selway 1 (5)(12)(17)(20)(21) (22)(27)(28)(29)	46° 04'	115° 25'	109	2.60	24	131	70.50	Western cedar	59%	166.8	18.40	
			57.73" N	19.69" W	207	2.60	24	131	70.50	Ponderosa pine	22%			
											Other willows	19%		
6	22	Selway 2 (5)(12)(17)(20)(21) (22)(27)(28)(29)	46° 05'	115° 32'	207	2.60	24	131	70.50	Western cedar	59%	166.8	18.40	
			29.02" N	15.49" W							Ponderosa pine	22%		
											Other willows	19%		
7	9	Johnson (5)(20)(21)(22)(28)	44° 52'	115° 30'	45	5.02	190	430	0.691	Grey alder	57%	70.64	351.9	
			33.17" N	26.12" W							Red osier dogw.	43%		
7	25	SF Salmon 1 (5)(20)(21)(22)(28)	44° 57'	115° 44'	54	2.50	38	113	34.56	Grey alder	57%	70.64	351.9	
			08.84" N	07.69" W							Red osier dogw.	43%		
7	26	SF Salmon 2 (5)(20)(21)(22)(28)	44° 57'	115° 44'	40	2.50	38	113	34.56	Grey alder	57%	70.64	351.9	
			03.45" N	03.38" W							Red osier dogw.	43%		

<sup>a</sup>Numbers, when present, refer to different reaches in the same river.

List of references at the end of the table

**Table 2.** Summary of collected data for the 35 river cross-sections. Group refers to similar characteristics of vegetation cover.

Group	ID	Site <sup>a</sup> (Ref.)	Latitude [° ' '' ]	Longitude [° ' '' ]	$B_f$ [m]	$S$ [% <sub>0</sub> ]	$D_{50}$ [mm]	$D_{90}$ [mm]	$Q_s$ [m <sup>3</sup> d <sup>-1</sup> ]	Vegetation characteristics and parameters			
										Species	Cover [%]	$\bar{\alpha}_g$ [cm <sup>2</sup> y <sup>-1</sup> ]	$\bar{\phi}_m$ [10 <sup>-3</sup> m <sup>-2</sup> ]
10	Kander (6)(7)(10)(19)(22)		46° 36'	007° 39'	88	13.3	76	287	3654	Norway spruce	46%	233.4	48.35
			17.00'' N	56.36'' E						Scots pine	31%		
27	Tay (1)(8)(9)(11)(22)(23)		56° 29'	003° 25'	166	2.19	1.14	5	153.2	Common alder	40%	59.60	49.53
			16.19'' N	35.11'' W						Downy birch	40%		
28	Virgin (5)(20)(21)(22)(28)		36° 53'	113° 55'	27	2.86	25	75	34.56	Salt cedar	62%	219.8	95.28
			33.21'' N	09.95'' W						Fremont cotton.	23%		
29	Wind I (5)(20)(22)(28)		43° 25'	109° 19'	192	3.34	22	75	267.8	Water birch	48%	41.31	67.27
			09.62'' N	56.54'' W						Spruce	36%		
30	Wind 2 (5)(20)(22)(28)		43° 18'	109° 08'	105	3.34	22	75	267.8	Narrow. cotton.	16%	41.31	67.27
			57.13'' N	00.02'' W						Water birch	48%		
									Spruce	36%			
									Narrow. cotton.	16%			

<sup>a</sup>Numbers, when present, refer to different reaches in the same river

(1) *Al-Ansari and McManus* [1979]; (2) *Andrews* [1980]; (3) *Andrews* [1984]; (4) *Ashworth and Ferguson* [1989]; (5) *Auble et al.* [2012]; (6) *BAFU Data* [2017]; (7) *BAFU GeoData* [2017];

(8) *Bates et al.* [2004]; (9) *Bryant and Gilvear* [1999]; (10) *Charlton et al.* [1978]; (11) *Claessens et al.* [2010]; (12) *Elliott and Anders* [2004]; (13) *Enescu et al.* [2016]; (14) *FLO Engineering* [1994];

(15) *Gilvear et al.* [2000]; (16) *Heins et al.* [2004]; (17) *Hoag* [2005]; (18) *Holnbeck* [2005]; (19) *Jud* [2009]; (20) *Mueller et al.* [2005]; (21) *Mueller and Pitlick* [2013]; (22) *Little and Viereck* [1971];

(23) *National River Flow Archive* [2017]; (24) *Novak* [2006]; (25) *Piedra* [2010]; (26) *Sharma and Parton* [2007]; (27) *Smith* [1999]; (28) *Water Data for the Nation* [2017]; (29) *Warner and Hendrix* [1984]