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► **To cite this version:**

Léa Kervroëdan, Romain Armand, Mathieu Saunier, Jean-François Ouvry, Michel-Pierre Faucon. Plant functional trait effects on runoff to design herbaceous hedges for soil erosion control. Ecological Engineering, 2018, 118, pp.143-151. 10.1016/j.ecoleng.2018.04.024 . hal-02365633

HAL Id: hal-02365633

<https://hal.science/hal-02365633>

Submitted on 15 Nov 2019

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1 **Plant functional trait effects on runoff to design herbaceous**
2 **hedges for soil erosion control**

3
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11
12
13 **Abstract**

14 Vegetation controls concentrated runoff and erosion in the European loess belt by
15 increasing hydraulic roughness and sediment retention. Studies of plant effects on runoff
16 velocity are usually based on a taxonomical characterisation and do not consider the
17 effects of aboveground plant functional traits in attempts to understand soil erosion by
18 water. This trait-based plant study investigates aboveground plant functional trait effects
19 of herbaceous hedges on the hydraulic roughness to understand soil erosion. Eight
20 aboveground functional traits were measured on fourteen indigenous and perennial plant
21 species (caespitose or comprising dry biomass in winter) from north-west Europe with a
22 high morphological variability. For each trait, density-weighted traits were calculated.

23 The effects of functional traits and density-weighted traits were examined using a runoff
24 simulator with four discharges. The leaf density and area, as well as density-weighted
25 stem and leaf areas, stem diameter and specific leaf area were positively correlated with
26 the hydraulic roughness. Generalised linear models defined the best combinations of traits
27 and density-weighted traits: (1) leaf density and leaf area, (2) density-weighted leaf area
28 and density-weighted projected stem area, and (3) density-weighted leaf area and density-
29 weighted stem diameter. Moreover, the effects of leaf density, leaf area and density-
30 weighted specific leaf area, varied depending on the discharge. This study is one of the
31 first characterisation of aboveground trait effects on hydraulic roughness and highlights
32 that vegetation with important stem density, diameter and leaf area plays a significant role
33 in minimising soil erosion. The selection of plant species can derive from these plant trait
34 effects to design reconstructed herbaceous hedges to minimise soil erosion.

35

36 **Key-words**

37 Aboveground functional traits; ecohydrological processes; hydraulic roughness; plant-
38 runoff interaction; sediment retention; soil erosion control

39

40 **1. Introduction**

41 Soil erosion by water is influenced by precipitation, soil texture and structure, slopes that
42 can generate intense discharges, and plant and litter covers which vary according to
43 cultural practices in cultivated areas. Intense runoff and soil erosion are frequently found
44 in north-western European catchments where the sloping loamy soils are intensively tilled
45 and cultivated with annual crops (Boardman and Poesen, 2006; Gobin et al., 2003). In the
46 European loess belt, erosion can be mitigated by both (1) tillage reduction and the

47 establishment of cover crops during sensitive seasons which increase the crop residue
48 quantity on soil surface and thus, reduce the rill and inter-rill soil erosion (Knapen et al.,
49 2007), and (2) establishment of vegetative barriers across the thalweg to mitigate rill and
50 ephemeral gully erosion (Richet et al., 2017). Richet et al. (2017) demonstrated the effects
51 of fascines (i.e. vegetative barriers made of bundles of stems) on hydraulic roughness and
52 soil erosion mitigation however, their short lifetime and high cost represent a main
53 limitation. Herbaceous hedges, defined as narrow strips of dense and stiff perennial
54 vegetation, constitute a major interest to develop vegetative barriers with a high efficiency
55 on the reduction of soil erosion at lower cost against concentrated flows (Dabney et al.,
56 1995; Yuan et al., 2009). Besides, herbaceous hedges composed of indigenous plant
57 species could offer other ecosystem services than regulating services such as the provision
58 of habitats and their ecological connectivity in these catchments (Ouin and Burel, 2002;
59 Smith et al., 2008).

60 The effect of herbaceous vegetation on runoff and soil erosion, have been studied over
61 the past decades (Haan et al., 1994; Lambrechts et al., 2014; Ludwig et al., 2005; Temple
62 et al., 1987). Blanco-Canqui et al. (2006), Dosskey et al. (2010), Lambrechts et al. (2014),
63 Le Bissonnais et al. (2005), Ruiz-Colmenero et al. (2013) and Stokes et al. (2014) noted
64 the direct effects of vegetation cover on splash detachment and inter-rill erosion
65 reduction. The impact of plant roots on infiltration capacity and resistance of soils to
66 erosion by water has been well documented (Berendse et al., 2015; Dabney et al., 2009;
67 De Baets et al., 2006; De Baets and Poesen, 2010; Gyssels et al., 2005; Isselin-Nondedeu
68 and Bédécarrats, 2007; Lambrechts et al., 2014). The influence of vegetation on sediment
69 retention was highlighted (Burylo et al., 2012; Dabney et al., 2009; Dillaha et al., 1989;
70 Haan et al., 1994; Isselin-Nondedeu and Bédécarrats, 2007; Lowrance et al., 1995). The

71 relationship between vegetation and sediment retention can be understood only if the
72 vegetation effect on hydraulic roughness, which is the frictional resistance due to the
73 contact of runoff with the vegetation, is characterised, as it is the main process with
74 gravity furthering sediment retention. This effect has been previously investigated
75 (Akram et al., 2014; Cantalice et al., 2015; Cao et al., 2015; Haan et al., 1994; Järvelä,
76 2002; Temple et al., 1987). The presence of herbaceous vegetation has positive impacts
77 on hydraulic roughness, as it reduces flow velocity and increases backwater depth (Akram
78 et al., 2014; Cantalice et al., 2015; Hussein et al., 2007), thereby increasing sediment
79 retention due to its linear relationship with backwater depth (Dabney et al., 1995; Hussein
80 et al., 2007; Meyer et al., 1995). Plant effects on hydraulic roughness are highly variable
81 among species and are difficult to explain without characterisation of all aboveground
82 morphological traits (Cantalice et al., 2015; Cao et al., 2015; Dabney et al., 1995). The
83 relationship between aboveground plant morphology and hydraulic roughness should be
84 specified to globally understand runoff and soil erosion processes.

85 One of the challenges to improving the understanding in plant and vegetation (e.g.
86 herbaceous hedges) effects on hydraulic roughness and soil erosion is the development
87 of a functional trait-based approach (Faucon et al., 2017). This approach, which allows
88 for characterising trait effects on ecosystem processes and services (Lavorel and Garnier,
89 2002), has been developed with the establishment of the relationship between the soil
90 detachment ratio and root length density for underground biomass (De Baets and Poesen,
91 2010; Mekonnen et al., 2016; Vannoppen et al., 2015). Concerning aboveground
92 characteristics, trait-based approaches highlighted the relationships between stem density,
93 diameter and stiffness, and between leaf area and density with sediment retention (Bochet
94 et al., 2000; Burylo et al., 2012; Mekonnen et al., 2016; Zhu et al., 2015). Because the

95 hydraulic roughness is one of the main process influencing sediment retention, plant
96 functional traits known to influence sediment retention could influence the hydraulic
97 roughness. Those traits, such as the stem and tiller density (Hayes et al., 1978; Isselin-
98 Nondedeu and Bédécarrats, 2007; Morgan and Duzant, 2008; Temple, 1982), stem
99 diameter (Bochet et al., 2000; Meyer et al., 1995; Morgan and Duzant, 2008), stem
100 stiffness (Dabney et al., 2009; Meyer et al., 1995), specific leaf area (Graff et al., 2005),
101 leaf area (Burylo et al., 2012) and leaf density (Lambrechts et al., 2014), should be
102 considered to specifically characterise the effect of aboveground traits on hydraulic
103 roughness. In addition to characterising vegetation effects on hydrological processes and,
104 notably, hydraulic roughness, the weight of traits in the vegetation should be considered
105 (Garnier and Navas, 2012) to improve the overall understanding of soil erosion.

106 Plant functional trait effects on hydraulic roughness should vary according to water
107 discharge and different hydraulic processes (Cao et al., 2015). Vieira and Dabney (2012)
108 showed that flow resistance of vegetation changed with flow depth. Temple et al. (1987)
109 and Van Dijk et al. (1996) found that for low flows, the mean flow velocity was dependent
110 on the vegetation density. However, for higher flows, when the flow depth was higher
111 than the deflecting vegetation height, the leaf structures had less impact and the flow
112 resistance was primarily dependent on the stem density and length and on the stem
113 diameter and stiffness (Meyer et al., 1995; Temple et al., 1987).

114 It is thus expected that high discharges would challenge the mechanical resistance
115 through the stiffness, the density and the diameter of the stems, while low discharges
116 would be impacted by the overall vegetation density. The challenge is to highlight plant
117 functional trait effects on hydraulic roughness at several discharges that are representative
118 of those present in catchments of north-west Europe.

119 This study of trait-based plant ecohydrology examined the relationship between
120 aboveground plant functional traits with the hydraulic roughness at different discharges
121 in fourteen perennial plant species presenting contrasting aboveground functional traits.
122 The objectives are (1) to highlight the major functional traits influencing hydraulic
123 roughness and (2) to examine the effect of discharges on the relationship between plant
124 functional traits and hydraulic roughness to improve the understanding of soil erosion and
125 select candidate species to create reconstructed herbaceous ecosystems to mitigate soil
126 erosion in north-west Europe.

127

128 **2. Materials and methods**

129 **2.1. Plant materials**

130 Fourteen plant species that display contrasting aboveground morphological traits were
131 chosen from 76 candidate species, resulting in six filters of selected functional types
132 involved in mitigation of soil erosion in north-west Europe applied to the 3,500
133 spermatophyte species from north-west Europe (Lambinon et al., 2012). These selective
134 filters were as follows: (1) Raunkiaer's life-form categories of "herbaceous
135 chamaephytes", "hemicryptophytes" and "geophytes", i.e., perennial herbaceous
136 vegetation that provide an effective soil cover during all seasons; (2) the presence of fresh
137 (i.e., herbaceous chamaephytes and caespitose hemicryptophytes) or dry (i.e., non-
138 caespitose hemicryptophytes and geophytes) biomass in winter when soil erosion is
139 observed in north-west Europe (Boardman and Poesen, 2006); (3) the presence of
140 rhizomes or stolon to ensure lateral spreading capacity and burial tolerance due to
141 sediment deposition; (4) vegetative height ≥ 20 cm, as it is the water maximal level in the
142 catchment in north-west Europe; (5) a broad ecological niche to select species able to

143 grow in several silty agricultural soils; and (6) non-weed species to prohibit their
144 expansion in agricultural territories of north-west Europe.

145 Thirteen of the tested species were from the list of candidates (*Carex sylvatica*, *Carex*
146 *flacca*, *Carex acutiformis*, *Carex pendula*, *Artemisia vulgaris*, *Origanum vulgare*, *Lolium*
147 *perene*, *Senecio jacobaea*, *Tanacetum vulgare*, *Festuca arundinacea*, *Dactylis glomerata*,
148 *Melica nutans*, *Phalaris arundinacea*) (Table 1). An exotic species, *Miscanthus sinensis*,
149 was also tested along the thirteen indigenous species as it is considered a model plant in
150 studies of plant hydraulic properties and erosion mitigation (Dabney et al., 2009). These
151 species, varying in leaf and stem traits (e.g., density, area and specific area – density,
152 diameter, specific density and dry matter content), were chosen to establish a range of
153 traits to highlight the effect of aboveground plant traits on hydraulic roughness. The
154 species were collected *in natura*, selecting only established individuals, and planted in
155 60 x 30 x 15 cm plots in early April 2016, creating 14 monospecific herbaceous hedges.
156 These vegetation plots consisted of a wooden frame with a 1.5 cm grid fence at the bottom
157 and were buried for three months prior the experiments to allow the full development of
158 the plants and roots. The plot design allowed for both plant growth and plot extraction for
159 the experiments in the runoff simulator.

160

161 **Table 1. List of the species used for the study and basic information.**

Category	Species name	Family	Life form	Vegetative height (m)
Graminoid	<i>Dactylis glomerata</i> L.	Poaceae	Hemicryptophyte	0.96 (\pm 0.11)
	<i>Festuca arundinacea</i> Schreb.	Poaceae	Hemicryptophyte	0.54 (\pm 0.14)
	<i>Lolium perenne</i> L.	Poaceae	Hemicryptophyte	0.34 (\pm 0.02)
	<i>Melica nutans</i> L.	Poaceae	Hemicryptophyte	0.28 (\pm 0.02)
	<i>Miscanthus sinensis</i>	Poaceae	Hemicryptophyte; Geophyte	1.03 (\pm 0.26)
	<i>Phalaris arundinacea</i> L.	Poaceae	Hemicryptophyte	0.49 (\pm 0.11)
Herb	<i>Artemisia vulgaris</i> L.	Asteraceae	Hemicryptophyte	0.96 (\pm 0.17)
	<i>Origanum vulgare</i> L.	Lamiaceae	Chamaephyte; Hemicryptophyte	0.48 (\pm 0.06)
	<i>Senecio jacobaea</i> L.	Asteraceae	Hemicryptophyte	0.98 (\pm 0.04)
	<i>Tanacetum vulgare</i> L.	Asteraceae	Hemicryptophyte	0.64 (\pm 0.07)
Sedge	<i>Carex acutiformis</i> Ehrh.	Cyperaceae	Hemicryptophyte	0.17 (\pm 0.03)
	<i>Carex flacca</i> Schreb.	Cyperaceae	Hemicryptophyte	0.31 (\pm 0.04)
	<i>Carex pendula</i> Huds.	Cyperaceae	Caespitose hemicryptophyte	0.23 (\pm 0.15)
	<i>Carex sylvatica</i> Huds.	Cyperaceae	Caespitose hemicryptophyte	0.12 (\pm 0.03)

The stem height values represent the mean values (\pm standard deviation) measured on the experimental plots.

162 **2.2. Plant morphological trait measurements**

163 Eight aboveground plant morphological traits (leaf – area, density and specific area; stem
164 – density, diameter, specific density, area and dry matter content), potentially involved in
165 increasing hydraulic roughness, were measured (Table 2) at three levels along the stem –
166 between 0 and 5 cm, 0 and 10 cm, and 0 and 20 cm – related to the variation of the water
167 flow depth. Sampling collection and process methods followed the guidelines from
168 (Pérez-Harguindeguy et al., 2013). The leaves and stems were wrapped in moist paper
169 and sealed in bags to limit water loss until the measures were complete, and they were
170 then dried at 70°C for 72 h.

171 **Table 2. List of the measured traits, their abbreviations and formulas used.**

Morphological trait	Abbreviation	Unit	Formula ^a	Abbreviation after density-weighting
Stem density	SD	stems.dm ⁻²	-	-
Leaf density	LD	leaves.dm ⁻²	-	-
Leaf area	LA	mm ²	-	WLA
Specific leaf area	SLA	mm ² .mg ⁻¹	$SLA = LA (Leaf\ mass_{dry})^{-1}$	WSLA
Stem diameter	SDm	mm	-	WSDm
Specific stem density	SSD	mg.mm ⁻³	$SSD = Mass_{oven\ dry} (Stem\ volume)^{-1}$	WSSD
Stem dry matter content	SDMC	-	$SDMC = Mass_{oven\ dry} (Mass_{fresh})^{-1}$	WSDMC
Projected stem area	SA	mm ²	$SA = L\ SDm$	WSA

^a Volume formulas used were (1) for cylindrical stems: $V = \pi L [(SDm) (0.5)]^2$ and (2) for triangular stems (*Carex* sp.): $V = [\sqrt{(3)}/4] SDm^2 L$ with L = height of the stem portion on which the concerned trait is measured

173 Trait measurements were performed within two 10 x 10 cm quadrats in each plot, to
174 ensure representative sampling. Stem density was measured within each quadrat, defining
175 pseudoculms in sedge species (Cyperaceae) and tillers in grass species as stems. Fresh
176 and dry leaves were counted to determine the leaf density at each level along the stems in
177 the quadrats. Specific leaf area (SLA) and leaf area were calculated from three mature
178 leaves per quadrat. The leaves were scanned while fresh using a 600 dpi resolution, and
179 the images were then analysed using the software Gimp 2.8 to determine the leaf area.
180 The SLA was calculated by dividing the leaf area by the oven-dry mass of the leaf. Stem
181 diameter, stem specific density and stem dry matter content were measured on three stems
182 per quadrat. Stem diameter (mm) was measured three times along each vertical level of
183 the fresh stem using a calliper. From the measurements of stem diameter, the projected
184 stem area was calculated using the rectangle area formula and represented the contact
185 area of a stem toward the flow direction. The stem specific density ($\text{mg}\cdot\text{mm}^{-3}$) was
186 calculated by dividing the oven-dry mass of the first 20 cm of the stem by the volume of
187 the stem, measured when still fresh. The volume of the stems was calculated using the
188 formula for the volume of a cylinder, except for the sledge species, which have triangular
189 stems, and for which we used the formula for the volume of a triangular prism. The stem
190 specific density of each height level along the stem was estimated using the volume of
191 each level by assuming the density was homogeneous within the stem section. The stem
192 specific density, representing the structural strength of a stem, was used as the estimation
193 of the plant resistance to the water flow (Burylo et al., 2012; Cornelissen et al., 2003;
194 Pérez-Harguindeguy et al., 2013). The stem dry matter content was calculated from the
195 ratio of the oven dry-mass of the first 20 cm of the stem and the fresh mass of the stem.
196 The mean values of the measured traits are listed in Appendices A1, A2 and A3.

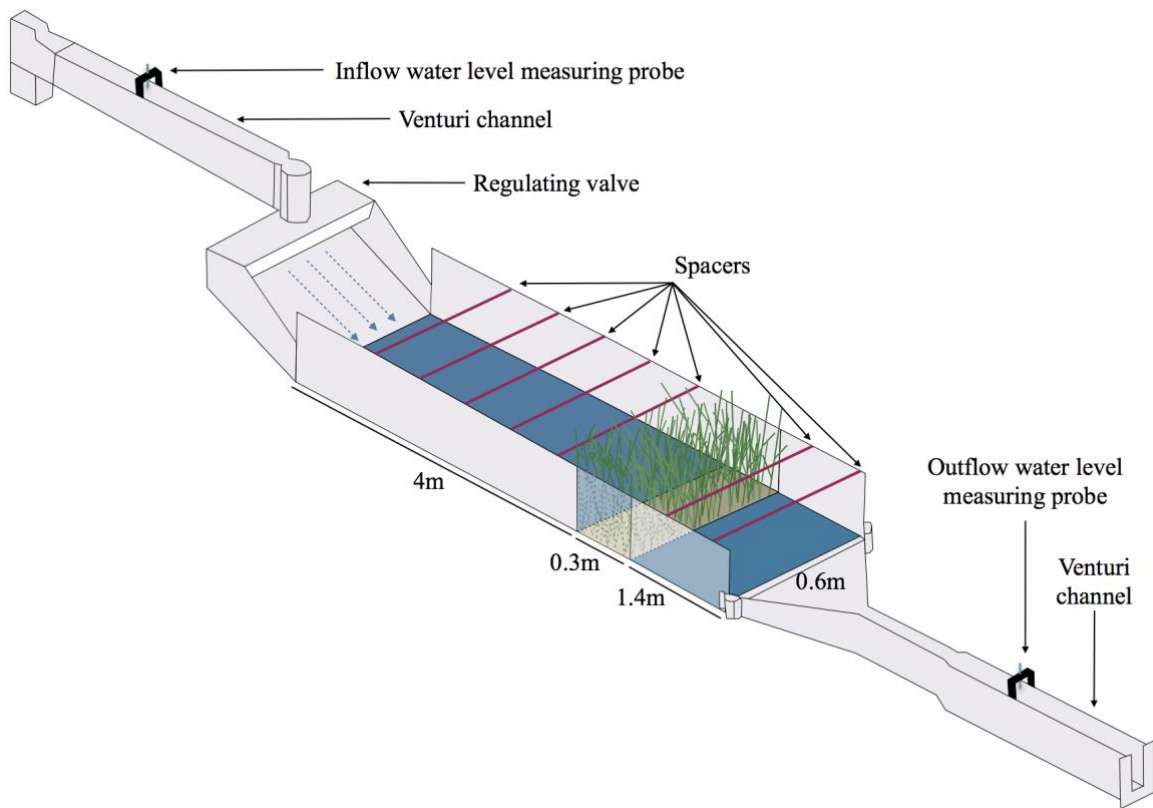
197 To characterise the effect of the herbaceous hedge on hydraulic roughness, the density-
198 weighted mean of the trait values was calculated for each trait as the mean value of the
199 trait multiplied by the proportion of the trait, here by the stem density for stem traits and
200 by leaf density for leaf traits. This method does not include plant cover, given that all
201 monospecific vegetation plot presented 100% cover and more precisely characterise the
202 abundance of traits from stem and leaf densities. These density-weighted traits were
203 determined for each vertical level along the stem (i.e. 0 – 5 cm, 0 – 10 cm and 0 – 20 cm).

204

205 **2.3. Hydraulic measurements**

206 We used the same runoff simulator as Richet et al. (2017) to quantify the effect of plant
207 morphological traits on hydraulic roughness (Fig. 1). The simulator allowed the
208 recreation of a flow at chosen discharges and the measurement of hydrological parameters
209 resulting from the presence of plants. The upper and lower parts of the simulator are
210 equipped with flowmeters made of Venturi channels with a flow range of 0.06 L.s⁻¹ to 6
211 L.s⁻¹, comprising ultrasound probes that measure the water level in the channel at ± 1.26
212 mm. This system was manufactured by ISMA, France (Richet et al., 2017). The water
213 was circulating within the system, with the aid of two pumps and a reservoir, in a closed
214 circuit. The central part of the simulator is a channel setup with two galvanised iron
215 sheets. The channel was 60 cm wide and 5.40 m long along a 5% slope. The entire channel
216 was waterproofed using a plastic tarpaulin to avoid any water loss during the experiments.
217 The tarpaulin was placed in order to obtain a smooth channel bottom and limit bottom
218 roughness as much as possible. The roughness of the tarpaulin was determined by
219 experiment using a control plot without any plants and represented a small percentage of
220 the roughness created by the plants (Appendix B). The vegetation was placed 4 m away

221 from the head of the channel, in a 17 cm deep rectangular hole to level the ground with
222 the flow and the slope. The tarpaulin used in the upper part of the channel was placed
223 continually underneath the plot and through the lower part of the channel to avoid water
224 loss by infiltration. The boundary effects were minimal as the plants were left in the
225 wooden frame where they grew, and a wooden plank was placed along each side the entire
226 channel. The small gap areas along the base of the planks and the bottom of the channel
227 were sealed using clay. Along the channel, 7 spacers were set up to measure the
228 topography of the channel bed and the water heights in the backwater and downstream of
229 the plot. Five were located upstream of the plants and two were located downstream.
230 Approximately 1.46 m from the channel head, the spacers were spaced at 0.75 m.



231

232 **Figure 1. Runoff simulator used during the study.**

233 The four discharges used in this study were 2, 4, 8 and 11 L.s⁻¹.m⁻¹ at ± 7%. The tested
234 discharges are observed approximately every 0.5, 1, 2 and 5 years, respectively, in 5 ha
235 catchments in the European loess belt with a 5 m-wide thalweg, as precised by Richet et
236 al. (2017). Both upstream and downstream discharges were continuously monitored.
237 Water level were measured when the upstream and downstream discharges were
238 equivalent. No infiltration occurred as the soil in the plots was saturated in water. The
239 backwater and downstream flow levels were measured using the spacers as elevation-
240 known baselines. The levels were determined by measuring the distance between the top
241 of the water flow and the spacer every 10 cm from the edges of the channel, corresponding
242 to seven vertical profiles.

243 To express the hydraulic resistance related to the plant presence, we used the unit stream
244 power (*USP*), a sediment transport capacity index (Govers, 1992; Yang, 1972). *USP* is
245 defined as the “energy dissipation per unit of time and per unit of weight of the flow”
246 (Govers, 1992), depending on its velocity and the slope:

$$247 \quad USP = VS \quad (1)$$

248 where *USP* is expressed in m.s⁻¹, *V* is the mean velocity (m.s⁻¹), and *S* is the channel slope
249 (m.m⁻¹) (Cao et al., 2015; Hessel et al., 2016; Morgan et al., 1998). The lower the *USP* is,
250 the greater the hydraulic roughness will be. The mean velocity was calculated using the
251 water levels measured at the closest spacer upstream of the plot. Govers (1990)
252 determined a *USP* critical value of 0.004 m.s⁻¹ that indicates that the threshold from which
253 soil is most likely to erode in the loamy soils found in the European loess belt. Govers
254 (1990) established this critical value for bare loess soils with a D₅₀ from 58 μm to 218
255 μm, at slopes ranging from 1° to 8° and for discharges varying from 0.2 to 10 L.s⁻¹.m⁻¹.
256 The *USP*, Manning coefficients and backwater depths are presented in Appendix B.

257

258 **2.4. Data analysis**

259 Principal component analysis (PCA) was conducted to examine the link between each
260 trait. Data used for the PCA included the measured traits in the two quadrats within the
261 plots. Generalised linear models (GLM) for the inverse-link gamma family were then
262 processed to examine the effect of plant morphological traits on the *USP* at each
263 discharge.

264 Another analysis using GLMs were then used to analyse the relationship between the *USP*
265 and the significant traits and density-weighted traits identified in the previous step
266 between 0 and 10 cm. These models were run separately for each discharge to highlight
267 differences of trait effects among the discharge levels. To avoid autocorrelation within
268 the models, traits and density-weighted traits were processed in separate models. Due to
269 the small sample size n and ratio $n/K < 40$ (where K the number of parameters used in the
270 models), second order Akaike's Information Criterion (AICc) and Δ AICc were used to
271 assess the model performance, as recommended in Burnham and Anderson (2002).
272 Δ AICc is the difference between the AICc of a model i and the model with the lowest
273 AICc (also characterised as the best model fit). Burnham and Anderson (2002) recognise
274 the models with a Δ AICc < 2 as models with substantial support, which are identified as
275 the best model fits in this study. Models with Δ AICc varying between 2 and 7, indicating
276 less support, were also analysed as recommended by Burnham et al. (2011). Akaike
277 weights (wAICc) were used in this study to assess the relative likelihood of the models,
278 as this indicates the probability of a model i being the best among the set of tested models
279 (Brown et al., 2011; Burnham and Anderson, 2002).

280 All the data in this study were analysed using the statistical software R (version 3.3.2).

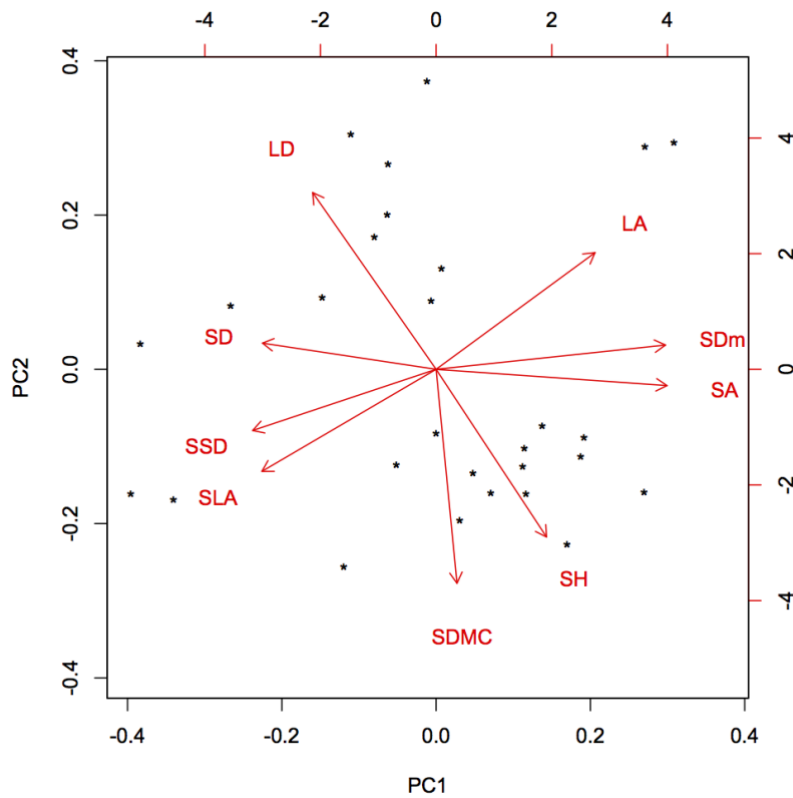
281

282 **3. Results**

283 **3.1. Variations of plant morphological traits**

284 Covariation among the seven traits of the 14 species studied were analysed using a PCA
285 (Fig. 2), which showed that the first two principal components explained 71.9% of the
286 variance. The first principal component (PC1) accounted for 47% of the total variance
287 and was associated with the projected stem area, the stem diameter and the stem density.
288 The variance of PC1 was explained by the leaf area, the stem specific density and the
289 specific leaf area. Two groups of variables were observed along the PC1 axis: the
290 projected stem area and the stem diameter on the positive end and the stem density on the
291 negative end. The second principal component (PC2) accounted for 24.9% of the total
292 variance and was explained by the stem dry matter content, which was found on the
293 negative end of the axis. The variance of PC2 was explained by the leaf density and the
294 stem height.

295



296

297 **Figure 2. Principal component analysis of nine morphological traits measured on 14**

298 **plant species.** PC1 explained 47% of the variance and PC2 explained 24.9%. LA = leaf

299 area, LD = leaf density, SA = projected stem area, SD = stem density, SDm = stem

300 diameter, SDMC = stem dry matter content, SLA = specific leaf area, SSD = stem

301 specific density. The vegetative stem height (SH) was added to the other traits for this

302 analysis.

303

304 **3.2. Effect of morphological traits on the Unit Stream Power**

305 The effects of traits on hydraulic roughness were analysed using GLMs to show the traits
306 affecting the *USP* at each discharge (Table 3). The leaf densities (0-5 cm and 0-10 cm)
307 were correlated to the *USP* for the four discharge levels. The leaf area had a significant
308 relationship with the *USP* at discharges Q1 and Q2, while the leaf density (0-20 cm) was
309 significant with the *USP* at discharges Q3 and Q4. The weighted leaf area (0-5 cm, 0-10
310 cm and 0-20 cm), the weighted projected stem area (0-5 cm, 0-10 cm and 0-20 cm), the
311 weighted stem diameter (0-5 cm, 0-10 cm and 0-20 cm) and the weighted SLA (0-5 cm)
312 were correlated to the *USP* at discharges Q1, Q2, Q3 and Q4. The weighted SLA (0-10
313 cm) influenced the *USP* at discharges Q2, Q3 and Q4.

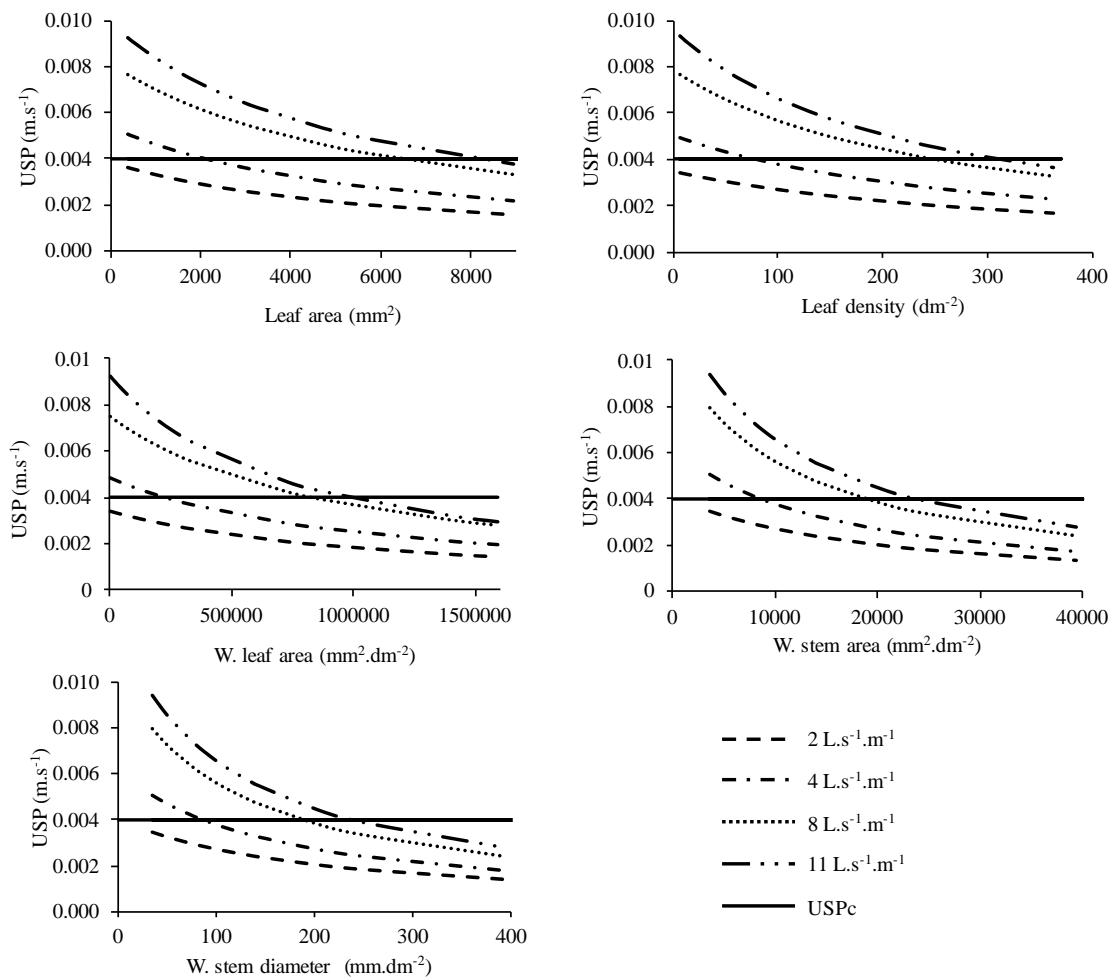
314

315 **Table 3. Morphological trait effects on USP for each discharge used.** Generalised
316 linear models (GLM) of each trait and density-weighted trait at each stem level in relation
317 to the *USP* for each discharge. LA = leaf area, LD = leaf density, SA = projected stem
318 area, SD = stem density, SDm = stem diameter, SDMC = stem dry matter content,
319 SLA = specific leaf area, SSD = stem specific density. The density-weighted traits were
320 named by adding “W” at the beginning of their existing abbreviations.
321

Traits	Level along the stem	Q1 = 2 L.s ⁻¹ .m ⁻¹		Q2 = 4 L.s ⁻¹ .m ⁻¹		Q3 = 8 L.s ⁻¹ .m ⁻¹		Q4 = 11 L.s ⁻¹ .m ⁻¹	
		AIC	β	AIC	β	AIC	β	AIC	β
LA		-158.15	0.04 *	-147.27	0.03 *	-131.38	0.02 ns	-125.83	0.02 ns
LD	0 - 5 cm	-159.11	1.33 *	-150.06	1.07 **	-135.45	0.78 **	-131.14	0.76 **
	0 - 10 cm	-157.68	0.81 *	-148.34	0.65 *	-134.21	0.49 *	-129.23	0.46 **
	0 - 20 cm	-154.49	0.44 ns	-145.21	0.37 ns	-131.54	0.29 *	-126.12	0.27 *
SA	0 - 5 cm	-152.71	0.46 ns	-141.33	0.22 ns	-126.83	0.11 ns	-120.93	0.1 ns
	0 - 10 cm	-152.55	0.22 ns	-141.25	0.11 ns	-126.78	0.05 ns	-120.87	0.05 ns
	0 - 20 cm	-151.70	0.08 ns	-140.75	0.02 ns	-126.51	0.0048 ns	-120.58	0.0037 ns
SD		-151.71	0.73 ns	-142.22	0.84 ns	-128.89	0.77 ns	-122.19	0.57 ns
SDMC		-153.37	-707.3 ns	-143.40	-571.4 ns	-130.15	-475.66 ns	-124.26	-429.54 ns
SDm	0 - 5 cm	-152.70	22.9 ns	-141.33	11.02 ns	-126.83	5.54 ns	-120.93	5.18 ns
	0 - 10 cm	-152.58	22.47 ns	-141.27	10.76 ns	-126.79	5.32 ns	-120.89	4.96 ns
	0 - 20 cm	-152.41	21.78 ns	-141.15	9.93 ns	-126.72	4.72 ns	-120.80	4.33 ns
SLA		-154.96	-7.87 ns	-142.59	-4.47 ns	-127.46	-2.39 ns	-121.92	-2.46 ns
SSD	0 - 5 cm	-153.46	-128.71 ns	-142.06	-75.4 ns	-127.63	-49.26 ns	-121.86	-46.93 ns
	0 - 10 cm	-153.64	-277 ns	-141.95	-151.2 ns	-127.38	-91.26 ns	-121.75	-93.63 ns
	0 - 20 cm	-153.33	-569.8 ns	-141.35	-251.1 ns	-126.88	-134.38 ns	-121.05	-134.77 ns
WLA	0 - 5 cm	-163.29	0.0004 **	-154.63	0.0003 **	-138.44	0.0002 **	-136.08	0.0002 **
	0 - 10 cm	-163.26	0.0003 **	-153.79	0.0002 **	-137.69	0.0001 **	-135.63	0.0001 **
	0 - 20 cm	-163.44	0.0002 **	-153.65	0.0001 **	-137.78	0.0001 **	-136.37	0.0001 **
WSA	0 - 5 cm	-161.43	0.02 **	-154.14	0.02 **	-141.02	0.02 **	-133.45	0.01 **
	0 - 10 cm	-160.97	0.01 **	-153.49	0.01 **	-140.30	0.0081 **	-132.81	0.0071 **
	0 - 20 cm	-158.44	0.0055 *	-149.75	0.0046 *	-136.37	0.0036 **	-129.07	0.0031 *
WSDMC		-151.38	1.72 ns	-141.76	2.31 ns	-128.25	2.14 ns	-121.66	1.51 ns
WSDm	0 - 5 cm	-161.43	1.25 **	-154.14	1.05 **	-141.02	0.82 **	-133.45	0.71 **
	0 - 10 cm	-161.06	1.24 **	-153.64	1.05 **	-140.46	0.82 **	-132.96	0.71 **
	0 - 20 cm	-160.46	1.21 *	-152.56	1.01 **	-139.27	0.79 **	-131.86	0.68 **
WSLA	0 - 5 cm	-157.33	0.06 *	-148.47	0.05 *	-134.37	0.04 *	-129.65	0.04 **
	0 - 10 cm	-154.34	0.03 ns	-145.19	0.03 *	-131.64	0.02 *	-125.92	0.02 *
	0 - 20 cm	-151.38	0.0058 ns	-141.71	0.0076 ns	-128.17	0.007 ns	-122.10	0.0061 ns
WSSD	0 - 5 cm	-151.10	0.12 ns	-141.05	0.22 ns	-127.32	0.23 ns	-121.02	0.15 ns
	0 - 10 cm	-151.07	0.19 ns	-141.03	0.41 ns	-127.32	0.45 ns	-120.99	0.28 ns
	0 - 20 cm	-151.04	0.23 ns	-141.00	0.8 ns	-127.33	0.91 ns	-121.00	0.58 ns

N = 14; AIC = Aikake's Information Criterion; β = regression coefficient; *** = p < 0.001; ** = p < 0.01; * = p < 0.05; ns = not significant. The significant correlations are indicated in bold.

323 From the results in Table 3, GLMs were used to highlight traits and density-weighted
324 traits (0-10 cm) that have a greater impact on the *USP* within the traits previously
325 identified as significantly impacting the *USP* (Fig 3, Table 4, Table 5). The GLMs for
326 single traits (Table 4) highlighted that the combination of leaf area and leaf density was
327 the best model fit for all discharges ($wAICc > 0.50$), although the leaf density was also a
328 good fit for the data at discharges Q3 and Q4 ($wAICc = 0.39$ and $wAICc = 0.34$,
329 respectively). The results of the density-weighted trait GLMs (Table 5) showed that
330 models $USP \sim WLA + WSA$ and $USP \sim WLA + WSDm$ were the best fit for all
331 discharges, with cumulative $wAICc$ ranging from 0.75 at discharge Q1 to 0.84 at Q4,
332 showing a growing significance along with the discharge gradient. However, the ranking
333 of importance changed with the discharges, as $USP \sim WLA + WSA$ was greater for
334 discharges Q1 and Q4, $USP \sim WLA + WSDm$ was greater for Q3 and both combinations
335 were equivalent for Q2.
336



337

338 **Figure 3. Relationship between *USP* and traits and density-weighted traits identified**
 339 **as the best fit to hydraulic roughness at 0 – 10 cm. *USPc* represents the threshold of**
 340 **0.004 m.s⁻¹ from which soil is likely to erode in loamy soils found in the European loess**
 341 **belt (Govers, 1990).**

342 **Table 4. Selected GLMs fitted to *USP* and two traits as estimation variables for each**
 343 **discharge used.** The models are sorted from the smallest $\Delta AICc$ to the highest $\Delta AICc$ at
 344 each discharge used.

345

Discharge	Models	AICc	$\Delta AICc$	wAICc
Q1 = 2 L.s ⁻¹ .m ⁻¹	USP ~ LA + LD	-158.68	0.0	0.707
	USP ~ LA	-155.75	2.9	0.164
	USP ~ LD	-155.28	3.4	0.129
Q2 = 4 L.s ⁻¹ .m ⁻¹	USP ~ LA + LD	-148.93	0.0	0.737
	USP ~ LD	-145.94	3.0	0.166
	USP ~ LA	-144.87	4.1	0.097
Q3 = 8 L.s ⁻¹ .m ⁻¹	USP ~ LA + LD	-132.34	0.0	0.512
	USP ~ LD	-131.81	0.5	0.393
	USP ~ LA	-128.98	3.4	0.096
Q4 = 11 L.s ⁻¹ .m ⁻¹	USP ~ LA + LD	-127.94	0.0	0.595
	USP ~ LD	-126.83	1.1	0.342
	USP ~ LA	-123.43	4.5	0.063
Full model was: USP ~ LA + LD; LD from (0-10 cm). AICc = second order Aikake's Information Criterion; see text for more details on $\Delta AICc$ and wAICc. LA = leaf area and LD = leaf density				

346 **Table 5. Selected GLMs fitted to USP and four density-weighted traits as estimation**
 347 **variables for each discharge used.** The models are sorted from the smallest ΔAICc to
 348 the highest ΔAICc for each discharge used.

Discharge	Models	AICc	ΔAICc	wAICc
Q1 = 2 L.s ⁻¹ .m ⁻¹	USP ~ WLA + WSA	-165.33	0.00	0.377
	USP ~ WLA + WSDm	-165.29	0.04	0.370
	USP ~ WLA + WSLA + WSDm	-161.93	3.40	0.069
	USP ~ WLA + WSA + WSLA	-161.92	3.41	0.069
	USP ~ WLA	-160.86	4.47	0.040
	USP ~ WLA + WSDm + WSA	-160.48	4.85	0.033
	USP ~ WSDm	-158.66	6.67	0.013
	USP ~ WSA	-158.57	6.76	0.013
Q2 = 4 L.s ⁻¹ .m ⁻¹	USP ~ WLA + WSA	-160.22	0.00	0.412
	USP ~ WLA + WSDm	-160.22	0.00	0.412
	USP ~ WLA + WSLA + WSDm	-156.45	3.77	0.063
	USP ~ WLA + WSA + WSLA	-156.38	3.84	0.060
	USP ~ WLA + WSDm + WSA	-155.16	5.05	0.033
Q3 = 8 L.s ⁻¹ .m ⁻¹	USP ~ WLA + WSDm	-143.44	0.00	0.405
	USP ~ WLA + WSA	-143.44	0.01	0.404
	USP ~ WLA + WSLA + WSDm	-138.78	4.67	0.039
	USP ~ WLA + WSA + WSLA	-138.73	4.71	0.038
	USP ~ WLA + WSDm + WSA	-138.39	5.06	0.032
	USP ~ WSDm	-138.06	5.39	0.027
	USP ~ WSA	-137.9	5.55	0.025
Q4 = 11 L.s ⁻¹ .m ⁻¹	USP ~ WLA + WSA	-140.87	0.00	0.423
	USP ~ WLA + WSDm	-140.86	0.02	0.419
	USP ~ WLA + WSLA + WSDm	-136.7	4.17	0.053
	USP ~ WLA + WSA + WSLA	-136.68	4.20	0.052
	USP ~ WLA + WSDm + WSA	-135.85	5.03	0.034
Full model was: USP ~ WLA + WSA + WSLA + WSDm. All variables are for traits (0-10 cm). AICc = second order Aikake's Information Criterion; see text for more details on ΔAICc and wAICc. WLA = weighted leaf area, WSA = weighted projected stem area, WSDm = weighted stem diameter, WSLA = weighted specific leaf area.				

349

350 **4. Discussion**

351 Contrary to processes of soil detachment by water flow (De Baets and Poesen, 2010;
352 Vannoppen et al., 2015) and sediment retention (Burylo et al., 2012), the effect of
353 morphological plant traits on hydraulic roughness corresponds to a lack of research to
354 understand the role of plant and vegetation on soil erosion. This study examined the
355 effects of plant morphological traits on hydraulic roughness for four discharges.

356

357 **4.1. Effect of morphological traits and density-weighted traits on hydraulic** 358 **roughness**

359 Stem and leaf traits influenced hydraulic roughness, given that they constitute a hydraulic
360 brake on water flows. However, some stem and leaf traits may have a greater effect on
361 hydraulic roughness. This study has highlighted that, among the considered aboveground
362 traits involved in soil erosion (i.e., leaf area, SLA, leaf density, stem density, stem
363 diameter, stem specific density, projected stem area and stem dry matter content), only
364 the leaf area and the leaf density presented a significant effect on hydraulic roughness.
365 The leaf traits have a better impact on hydraulic roughness than stem traits, regarding
366 non-weighted traits. The GLMs showed that the combination of leaf density and leaf area
367 better explained the effect on hydraulic roughness than these traits alone for any discharge
368 used. Plant individuals with better trade-off between leaf density and leaf area, meaning
369 high leaf density and long leaves, such as some graminoid species, would have a great
370 impact on mitigating the unit stream power and thus increase hydraulic roughness. These
371 results are in agreement with other studies highlighting the efficiency of several
372 graminoid species in soil erosion mitigation (Isselin-Nondedeu and Bédécarrats, 2007;
373 Morgan, 2004). The absence of the stem density effect on hydraulic roughness is not in

374 agreement with the literature where the stem density is considered a main trait impacting
375 flow velocity and soil erosion (Isselin-Nondedeu and Bédécarrats, 2007; Mekonnen et al.,
376 2016; Meyer et al., 1995; Morgan and Duzant, 2008; Temple et al., 1987). This
377 contradiction could be explained by the lack of a standard characterisation of all stem and
378 leaf traits involved in hydraulic roughness and soil erosion (e.g. defining the tillers and
379 pseudoculms as stems when characterising the stem density). The stem density is one of
380 the main traits included in hydraulic and soil erosion models such as VFSSMOD (Muñoz
381 Carpena and Parsons, 2014) and in studies focusing on the relationship between
382 vegetation and hydraulic roughness or sediment retention (Morgan, 2004; Temple, 1982;
383 Van Dijk et al., 1996; Xiao et al., 2011), which could be improved by considering the
384 effect of other stem traits (e.g., stem diameter). In the trait-based approach, the importance
385 of stem density in the plant-hydraulic roughness relationship lays in its use in the
386 calculation of weighted stem trait values in the vegetation. Indeed, this approach
387 highlighted that mainly density-weighted traits influenced hydraulic roughness.
388 Specifically, all the GLMs included weighted leaf area, indicating its great importance in
389 the increase of hydraulic roughness. Projected stem area or stem diameter showed no
390 significance on the hydraulic roughness at the trait level but, by considering weighted
391 stem traits, weighted projected stem area and weighted stem diameter showed highly
392 significant effects on the unit stream power. The GLMs showed that the best fit model
393 was WSA + WLA (weighted projected stem area + weighted leaf area) as these traits
394 represent the interception area of the leaves and stems with the water flow in the
395 vegetation, i.e., a hydraulic brake. As the stem diameter, projected stem area and leaf area
396 were negatively associated with the stem density, trade-offs among these stem and leaf
397 traits can be considered to improve herbaceous hedge effects on hydraulic roughness. The

398 effect of weighted SLA, when associated with weighted leaf area and weighted stem
399 diameter or weighted leaf area and weighted projected stem area, was also observed ($3 <$
400 $\Delta AICc < 5$). Overall, vegetation presenting the best trade-off between stem density and
401 weighted stem diameter, as well as between leaf density and leaf area, will have a greater
402 efficiency to increase hydraulic roughness. Herbaceous hedges that present these
403 weighted leaf and stem traits would be partly composed of graminoid species, given that
404 these present large leaf density, leaf area, stem diameter and a greater hydraulic roughness
405 than non-graminoid species (Isselin-Nondedeu and Bédécarrats, 2007). Stem and leaf
406 densities should be considered to calculate weighted-traits in herbaceous hedges and
407 quantify the effect on soil erosion. Characterisation of trait weights in herbaceous hedges
408 vegetation allowed to highlight the main morphological aboveground traits and their
409 combinations involved in hydraulic roughness, as well as the importance of stem density
410 as a plant marker to examine the effect of vegetation on runoff. As a result, this trait-
411 based approach can be effectively applied at the vegetation level to understand and model
412 runoff and soil erosion.

413

414 **4.2. Effects of morphological traits on hydraulic roughness depending on runoff** 415 **processes**

416 Flow rate variations can trigger different soil-plant-water processes (Dabney et al., 2004;
417 Temple et al., 1987; Vieira and Dabney, 2012). The results here are consistent with the
418 hypothesis that the influence of aboveground traits on hydraulic roughness can change
419 with the discharge. The effect of leaf density (0-20 cm) and leaf area on hydraulic
420 roughness varied with the discharge. The results showed the importance of leaf density
421 in increasing hydraulic roughness at higher discharges ($\Delta AIC < 2$). However, for lower

422 discharges, a combination of leaf area and leaf density should be considered rather than
423 the traits alone. The results for the leaf area are in accordance with the one found by
424 Temple et al. (1987) showing a decreasing impact of the leaf structure with an increasing
425 discharge. At a small discharge ($2 \text{ L}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$), weighted SLA (0-10 cm) did not present an
426 effect on the hydraulic roughness, but a positive influence was observed at $4 \text{ L}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$.
427 Differences in the influence of leaf density and weighted SLA among the discharges may
428 be interpreted as the water depth being too low to enter into contact with all the leaves
429 between 0 and 20 cm of each individual and with large SLA until 5 cm of the vegetation
430 at small discharges. Herbaceous hedges, playing a key role in hydraulic roughness,
431 presents the best trade-off between stem density and diameter, as well as leaf density and
432 area at low discharges, and with increasing water discharge, larger basal leaf density and
433 basal SLA. This study indicates that some trait and density-weighted trait effects on
434 hydraulic roughness are linked to the flow water level. The characterisation of these
435 effects according to flow depth constitutes an advance to model water flows and soil
436 erosion in ecosystems and landscapes.

437

438 **4.3. Consequences on sediment retention**

439 As hydraulic roughness is linked to sediment retention and transport capacities (Dabney
440 et al., 2009; Isselin-Nondedeu and Bédécarrats, 2007; Lambrechts et al., 2014; Munoz-
441 Carpena et al., 1999), plant morphological traits, which have positive effects on hydraulic
442 roughness, can be discussed with studies highlighting plant trait effects on sediment
443 retention. Indeed, results showed the positive effect of the leaf area on hydraulic
444 roughness, whereas there was no effect of stem specific density at small discharges, such
445 as $2 \text{ L}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$, which is consistent with Burylo et al. (2012) on the sediment retention

446 capacity for more intense erosion processes. Results display the greater impact of density-
447 weighted traits, which were previously not considered in studies on plant trait effects on
448 sediment retention. The density-weighted trait approach is therefore important in
449 understanding the plant-soil interaction involved in soil erosion.
450 Application of this trait-based approach in ecohydrology involves using the results to
451 manage the reduction of soil erosion. Use of the unit stream power allows to characterise
452 the plant efficiency with regard to sediment retention, with a critical *USP* (*USP_c*) value
453 of 0.004 m.s⁻¹ determined by (Govers, 1990), which indicates the threshold from which
454 soil is most likely to erode in loamy soils found in the European loess belt. From identified
455 traits and density-weighted traits presenting an effect on hydraulic roughness and their
456 values (*USP* < 0.004 m.s⁻¹) plant species selection could be performed to create new
457 herbaceous ecosystems that will be efficient to reduce runoff and further sediment
458 retention on degraded areas (e.g., bare soils in degraded agroecosystems, urban and
459 mining habitats) (Fig. 3).

460

461 **5. Conclusions**

462 This trait-based ecohydrology study allows the identification of important plant traits that
463 influence the hydraulic roughness. The results indicate the stronger effect of density-
464 weighted traits, showing that communities with the best trade-offs between stem density,
465 diameter and leaf area are the key to mitigate soil erosion. This new knowledge in the
466 relationship between plant functional traits with hydraulic roughness and soil erosion
467 constitutes a new advancement for modelling vegetation effects on soil erosion and
468 creating new herbaceous ecosystems in degraded areas (e.g. bare soils of agroecosystems,
469 mining and urban habitats). These newly reconstructed herbaceous ecosystems will play

470 an important role in soil erosion mitigation. Future work should (1) include these
471 relationships between aboveground traits and hydraulic roughness in existing models to
472 estimate the transport and sediment retention capacities of flows and design herbaceous
473 hedges to mitigate soil erosion and (2) examine the effect of functional diversity on runoff
474 and soil erosion, as it could influence hydraulic roughness by ecologically complementing
475 aboveground biomass and, more precisely, by limiting vegetation lodging.

476

477 **Acknowledgements**

478 The authors thank the funders of this study: Agence de l'Eau Seine-Normandie (Seine-
479 Normandie Catchment Agency), Région Normandie (Normandy council) and ANRT
480 (National Association for Technological Research). Special acknowledgements are given
481 to Dr. Yves le Bissonnais and Dr. Freddy Rey for their scientific comments on the
482 methods of our study and M. Jean-Baptiste Richet for his insightful comments and
483 technical advice.

484

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