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1 **ACCEPTED**

2 **Effects of plant traits and their divergence on runoff and sediment**  
3 **retention in herbaceous vegetation**

4  
5  
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13  
14  
15 **Key-words**

16 Aboveground functional traits; Plant-soil-runoff interactions; Sediment transport; Sediment  
17 trapping and deposition; Soil erosion control

18  
19  
20 **Abstract**

21 Aims

22 Plant species diversity impacts ecosystem processes, but its effects on runoff and soil erosion  
23 are not fully understood. Herbaceous vegetation control concentrated runoff and soil erosion  
24 through the increase of hydraulic roughness which leads to sediment retention. This study aims

25 to investigate the effect of aboveground traits and their divergence (i.e., stem diameter and  
26 density, and leaf area and density) on hydraulic roughness and sediment retention in plant  
27 communities.

## 28 Methods

29 Runoff experimentations were performed, using a sediment input, on three mono-specific and  
30 one multi-specific conditions composed of plant species with contrasting traits furthering  
31 hydraulic roughness and sediment retention.

## 32 Results

33 No effect of trait diversity was found on the hydraulic roughness and sediment retention; which  
34 would be explained by the absence of an optimal space use by the traits involved in the increase  
35 of the hydraulic roughness. The dominant effect of the community-weighted traits in the plant  
36 community drives the effects of the vegetation on the hydraulic roughness and sediment  
37 retention.

## 38 Conclusion

39 This absence of positive effects of the trait diversity on hydraulic roughness and sediment  
40 retention constitutes an important knowledge to model runoff and soil erosion processes and to  
41 design herbaceous infrastructures for soil erosion control.

42

43

## 44 **Introduction**

45 Soil-plant interactions play a key role in the reduction of runoff and soil erosion (Styczen and  
46 Morgan 1995). The effects of plant functional traits (i.e., ‘morpho-physio-phenological traits  
47 which indirectly impact fitness via their effects on growth, reproduction and survival’ (Violle  
48 et al. 2007)) in herbaceous vegetation have been studied on different processes generating and

49 favouring runoff and soil erosion (Morgan 2004; Hussein et al. 2007; Isselin-Nondedeu and  
50 Bédécarrats 2007; Burylo et al. 2012; Stokes et al. 2014; Liu et al. 2016; Mekonnen et al. 2016).  
51 In vegetation patches, notably under temperate climates, concentrated runoff and soil erosion  
52 are mainly controlled by the hydraulic roughness of herbaceous vegetation (i.e. frictional  
53 resistance of the vegetation in contact with the flow) which induces sediment retention by  
54 slowing the flow velocity (Meyer et al. 1995; Akram et al. 2014). More the flow velocity will  
55 be reduced, more the quantity of sediments which will be retained by the vegetation will  
56 comprise a wider variety of particle sizes, and especially smaller particles (Haan et al. 1994;  
57 Syversen and Borch 2005). This indirect effect of the plant traits on the fractions of sediment  
58 particles retained constitutes an important feature to understand the vegetation effects on soil  
59 erosion, notably regarding the environmental consequences as the smaller sediment particles  
60 are the most impacting ones regarding pollutant dispersion and water quality degradation  
61 (Syversen and Borch 2005; Liu et al. 2008; Lambrechts et al. 2014). The effects of functional  
62 traits on hydraulic roughness and sediment retention have been studied over the past decades,  
63 showing the effects of aboveground biomass, projected stem area (i.e. stem area towards the  
64 flow direction), stem density and diameter as well as leaf area and density (Burylo et al. 2012;  
65 Zhu et al. 2015; Mekonnen et al. 2016; Kervroëdan et al. 2018). Some of these traits are found  
66 negatively correlated (e.g. leaf area and density), implying that trait diversity and divergence  
67 could have a better impact on hydraulic roughness and sediment retention by exerting  
68 complementary effects of the traits (Kervroëdan et al. 2018). Positive effects of the trait  
69 aggregation, due to trait divergence – or functional diversity – are driven by the  
70 complementarity of the traits which leads to a better space occupation inducing greater effects  
71 of the community structure and distribution on soil erosion reduction (Zhu et al. 2015). On the  
72 other hand, when no effects of the trait diversity are observed, it is the community-weighted  
73 traits (i.e. the mean of the trait values in the plant community) that are leading the effects on

74 the hydraulic roughness and sediment retention (Erktan et al. 2013; Zhu et al. 2015). As for  
75 several other ecosystem processes, plant species diversity integrating contrasting plant  
76 functional traits can influence the processes involved in soil erosion (Naeem et al. 1994; Tilman  
77 2001a; Martin et al. 2010; Zhu et al. 2015). The mechanisms driving the effects of plant species  
78 diversity on ecosystem processes can follow two non-exclusive hypotheses (Loreau 2000;  
79 Garnier et al. 2016). The selection hypothesis stipulates that one or more dominant species in  
80 the community would increase the overall productivity and efficiency of the community. On  
81 the other hand, the complementarity hypothesis specifies that plant species diversity effects on  
82 ecosystem processes result from a more complete space and resource uses by the trait  
83 divergence composing the plant community (Loreau and Hector 2001; Fargione et al. 2007).  
84 The relationships between plant trait diversity and soil erosion processes have been studied,  
85 mostly focussing on the effects of non-herbaceous plant roots on soil stabilisation and  
86 vegetation patch pattern impact on erosion rates (Gyssels et al. 2005; Bautista et al. 2007; Pohl  
87 et al. 2009; Martin et al. 2010; Berendse et al. 2015; Hou et al. 2016). However, the effects of  
88 trait diversity on sediment retention are not well known and can be contrasting (Martin et al.  
89 2010; Erktan et al. 2013; Zhu et al. 2015; Hou et al. 2016). Studies focussing on the effects of  
90 functional diversity on sediment retention and erosion rates showed controversial effects on the  
91 functional diversity (i.e., ‘the value, range, and relative abundance of plant functional traits in  
92 a given ecosystem’ (Tilman 2001b; Díaz et al. 2007)) (Erktan et al. 2013; Zhu et al. 2015).  
93 Influenced by neighbouring, the interspecific differences in functional traits among diverse  
94 plant communities have been found to impact positively soil erosion reduction (Zhu et al. 2015).  
95 These debated results stress the need to deepen the knowledge on the effects of the trait diversity  
96 in herbaceous vegetation on concentrated runoff and soil erosion to increase hydraulic  
97 roughness and sediment retention.

98 This trait-based plant-soil study aimed to examine the effects of the traits and their divergence  
99 on the hydraulic roughness and sediment retention by characterising the quantity of retained  
100 sediments and their sizes. We hypothesised that the aggregation of contrasting traits involved  
101 in the increase of the hydraulic roughness would induce a better aboveground space use and a  
102 better sediment retention. The traits and their divergence, which would have a greater effect on  
103 the hydraulic roughness, would lead to a wider variety of the size of the retained sediments by  
104 the multi-specific plant communities.

105

106

## 107 **Materials and methods**

### 108 **Plant material**

109 Three herbaceous species presenting contrasting aboveground morphological traits furthering  
110 the hydraulic roughness were selected from a list of 76 potential candidate species of indigenous  
111 plants from north-west Europe. This list was obtained by applying six criteria to the 3500  
112 spermatophyte species of north-west Europe (Lambinon et al. 2012) based on the identified  
113 functional types influencing runoff and soil erosion in this phytogeographical territory  
114 (Kervroëdan et al. 2018): (1) the Raunkiaer's life-form categories "herbaceous chamaephytes",  
115 "hemicryptophytes" and "geophytes" which select perennial herbaceous species with an  
116 effective soil cover all year; (2) the presence of biomass during winter, when soil erosion is  
117 observed at its highest in north-west Europe (Boardman and Poesen 2006), either dry (i.e., non-  
118 caespitose hemicryptophytes and geophytes) or fresh (i.e., herbaceous chamaephytes and  
119 caespitose hemicryptophytes); (3) the presence of stolon or rhizomes which ensure a lateral  
120 spreading growth pattern forming a homogenous cover and burying tolerance towards sediment  
121 deposition; (4) a vegetative height  $\geq 20$  cm to avoid any submergence of the vegetation by the  
122 water flow and ensure the efficiency towards concentrated flows (Dillaha et al. 1989), as the

123 water maximal level is 20 cm in north-west European catchments; (5) a broad ecological niche  
124 which guarantee the plants development within a wide gradient of soil conditions and (6) the  
125 non-invasiveness of the plants which select non-weed species and avoid the plant spreading  
126 into agricultural fields.

127 To restrict the competition for light, the species were chosen considering their vegetative height  
128 range with a minimal height comprised between 40 and 70 cm. The species *Carex pendula*  
129 Huds., *Tanacetum vulgare* L. and *Festuca arundinacea* Schreb. were tested under three  
130 monospecific and one multi-specific communities (Fig. 1), each condition comprising three  
131 replicates. Only one multi-specific condition (comprising the three species) was tested as the  
132 aim of this study was to examine the effect of the trait diversity on the hydraulic roughness and  
133 sediment retention using contrasting traits. The multi-specific communities were composed of  
134 the three species and presented a high functional diversity, with a functional divergence (FDis,  
135 with a range between 0 and 1) of 0.88 ( $\pm 0.04$ ) (Villéger et al. 2008).

136

### 137 **Experimental site design**

138 The plots were implanted at the bottom edge of a loamy field cultivated with winter wheat  
139 located in the municipality of Drosay, Normandy, France (Fig 2.A). The soil, defined as  
140 Luvisol, was characterised by 12.5% ( $\pm 0.66\%$ ) clay, 64.3% ( $\pm 0.84\%$ ) silt and 23.2% ( $\pm 0.64\%$ )  
141 sand with a pH of 5.3 ( $\pm 0.1$ ), 2.1% ( $\pm 0.19\%$ ) of organic matter content and a crusting index of  
142 1.8 ( $\pm 0.08$ ).

143 In October 2016, one year *prior* experiments, the plants were planted in 1m<sup>2</sup> plots with a density  
144 of 53 young plants.m<sup>-2</sup> (Fig. 1). The multi-specific plots were planted with the same proportion  
145 of each species and the young plants were placed so young plants of the same species would  
146 not be next to each other. A control condition, with no vegetation, was also tested with three  
147 replicates to compare the effects of the traits between each species. Each of the 15 plots was



148 randomly distributed along a 50m strip and 2m were left between each plot to allow movement  
149 and limit plant spreading in the next plot (Fig. 2.B).

150

### 151 **Hydraulic measurements**

152 A runoff simulator (Fig. 3) generating a flow at set discharges in controlled conditions was used  
153 to performed the experiments in October and November 2017 (Richet et al. 2017; Kervroëdan  
154 et al. 2018). The simulator was composed of three parts, two Venturi channels with ultrasound  
155 probes measuring the water level in the channels ( $\pm 1.26$  mm) on both ends of a channel where  
156 measurements were performed. The central channel was a 5.2 m by 0.90 m stainless steel  
157 channel with a 1.2 m bottomless part where the vegetation was located. The channel slope was  
158 measured for each plot using an automatic rotating laser (Geo Fennel EL 515plus) and was  
159 adjusted to 4.90% ( $\pm 0.13\%$ ), using wooden planks to ensure stability during experiments. The  
160 backwater levels in front of the plots were measured using six spacers placed upstream the  
161 plants. The closest spacer from the plants was 13 cm away, the next two were spaced by 25 cm,  
162 the forth spacer was 50 cm away from the third and the last two were spaced by 75 cm. Each  
163 spacer was levelled and their elevations were measured and used as elevation-known baselines  
164 for the water level measurements.

165 The hydraulic parameters which were measured during the experiments were the flow discharge  
166 and the water levels in the backwater area. The discharge used for the experiments was  $3.6 \text{ L.s}^{-1}$   
167  $\text{m}^{-1}$  ( $\pm 0.06 \text{ L.s}^{-1}.\text{m}^{-1}$ ), and was continuously monitored using the upstream and downstream  
168 flowmeters. The water level measurements were carried out when the upstream and  
169 downstream discharges were equivalent. The perpendicular distance between the bottom of the  
170 spacer and the top of the water flow was measured with an aluminium ruler. Ten water level  
171 measurements were done on each spacer, every 10 cm along the spacer from one channel edge

172 to the other. All the water level determinations were undertaken using clear water flows (Table  
173 1).

174 The unit stream power (USP,  $\text{m}\cdot\text{s}^{-1}$ ) was used to characterise the hydraulic roughness (Yang  
175 1972; Govers 1992). Often used as a sediment transport capacity index, it defines the energy  
176 dissipation of the flow, per unit of time and per unit of weight, and depends on the mean flow  
177 velocity ( $V$ ,  $\text{m}\cdot\text{s}^{-1}$ ) and the slope ( $S$ ,  $\text{m}\cdot\text{m}^{-1}$ ) (Govers 1992):

$$178 \quad USP = VS \quad (1)$$

179 The USP was calculated based on the water levels measured on the closest spacer to the  
180 vegetation. The USP is negatively related to the hydraulic roughness: the lower it is, the higher  
181 the hydraulic roughness will be.

182

### 183 **Sediment retention**

184 In June 2017, soil in the experimental site was taken off, sifted at 2 mm and stored until October  
185 2017. *Prior* the experiments, the sediments were dried at 40°C for 72h and stored in sealed  
186 containers. After conducting the water level measurements, sediments were integrated into the  
187 flow in order to characterise the trait diversity effect on sediment retention capacity. The  
188 sediment concentration was at  $11 \text{ g}\cdot\text{L}^{-1}$  ( $\pm 0.36 \text{ g}\cdot\text{L}^{-1}$ ) at a discharge of  $3.6 \text{ L}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$  ( $\pm 0.09 \text{ L}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$ ).  
189  $^1\cdot\text{m}^{-1}$ ). The sediment concentration and discharge used were chosen in order to analyse the  
190 effects of traits and their divergence in plant communities on frequent erosional episodes (e.g.  
191 annually) observed in the upper parts of catchments located in the European loess belt. Indeed,  
192 the sediment concentration of  $11 \text{ g}\cdot\text{L}^{-1}$  represents more than 75% of the sediment concentrations  
193 measured in small catchments and in the upper parts of the catchments in the European loess  
194 belt (Van Dijk et al. 1996; Cerdan et al. 2002; Le Bissonnais et al. 2004; Delmas et al. 2012;  
195 Richet et al. 2017).

196 The experiment lasted 3 min of sediment input and was followed by 30 sec of clear water to  
197 allow the last sediments to be transported. The extra 30 sec of clear water did not significantly  
198 influence the sediment particles detachment and their transport in the flow downstream the  
199 vegetation (Supplementary material). In order to estimate the quantity of sediment passing  
200 through the vegetation, a 250 ml flow sample was taken every 15 sec, from the sediment input  
201 to the end of the experiment. After the test run, the sediments deposited in the channel were  
202 collected. All the sampled sediments were oven-dried at 105°C for 48h and weighted. The  
203 quantity of trapped sediments in the vegetation was estimated from calculation. Particle  
204 granulometry was analysed using a LS 13 320 Beckman Coulter particle sizing analyser for the  
205 sediments deposited in the channel (upstream) and the ones downstream the vegetation.

206 The total sediment quantity downstream the vegetation was calculated using a sequential  
207 calculation method, from each sample collected. The quantity trapped within the vegetation  
208 ( $S_{\text{within}}$ ) was estimated as followed:

$$209 \quad S_{\text{within}} = S_{\text{input}} - (S_{\text{upstream}} + S_{\text{downstream}}) \quad (2)$$

210 where  $S_{\text{input}}$  is the total quantity of sediments integrated into the flow,  $S_{\text{upstream}}$  is the quantity  
211 deposited in the channel and  $S_{\text{downstream}}$  the quantity which passed through the vegetation.

212 The sediment retention capacity represented the quantity of sediments upstream and within  
213 the vegetation:

$$214 \quad S_{\text{retention}} = S_{\text{upstream}} + S_{\text{within}} \quad (3)$$

215

### 216 **Leaf and stem trait measurements**

217 Six aboveground plant morphological traits (stem – density, diameter, projected area; leaf –  
218 density, area and specific area), known to influence the hydraulic roughness and sediment  
219 retention (Kervroëdan et al. 2018), were measured on three levels along the stem: between 0  
220 and 5 cm, 0 and 10 cm and 0 and 20 cm. Sampling collection, samples conservation and

221 analyses methods were conducted following the standardised guidelines from (Pérez-  
222 Harguindeguy et al. 2013). The leaves were collected in sealed bags with moist tissue until  
223 measurements were performed and then, dried at 70°C for 72h. The traits were all measured  
224 within one quadrat (10 by 10 cm) per monospecific community plot and one quadrat per species  
225 within the multi-specific community plots, due to the homogeneous plant cover within the plots.  
226 The leaf density (leaves.m<sup>-2</sup>) was measured for each level along the stems by counting fresh  
227 and dry leaves. The leaf area (mm<sup>2</sup>) and specific area (mm<sup>2</sup>.mg<sup>-1</sup>) were determined using six  
228 representative leaves, scanned at 600dpi resolution, and the images were analysed using Gimp  
229 2.8. Pseudoculms for sedges species (Cyperaceae) and tillers for grass species were counted  
230 with the stems to measure the stem density (stems.m<sup>-2</sup>). The stem diameter (mm) was measured  
231 for each level on three representative stems and was used to calculate the projected stem area  
232 (mm<sup>2</sup>), using the rectangle area formula. The aboveground biomass (g) was estimated by  
233 collecting a 50 x 50 cm quadrat in each plot and dried during 72h at 70°C. The species biomass  
234 in the multi-specific plots were separated in order to determine the biomass productivity of each  
235 species.

236 Moreover, a density-weighted trait was calculated for each trait by multiplying the (1) leaf traits  
237 with the leaf density and (2) stem traits with the stem density; which corresponded to the density  
238 value of the traits and were dissociated from the traits with a “D” at the front of the trait  
239 appellations.

240

## 241 **Characterisation of the trait diversity effects on the hydraulic roughness and sediment** 242 **retention**

243 All multi-specific plots were planted with an equal abundance of each species, although these  
244 abundances changed through the year to experiments. The abundance (%) of each species was  
245 estimated for each multi-specific plot.

246 The community-weighted traits (CWT) were calculated for each trait in the multi-specific plots  
247 by weighting each trait with the species abundance (Díaz et al. 2007; Violle et al. 2007):

$$248 \quad CWT_i = \sum_{k=1}^{n_i} A_{k,i} T_{k,i} \quad (5)$$

249 with  $CWT_i$  being the community-weighted value of the trait in the community  $i$ ,  $A_{k,i}$  and  $T_{k,i}$   
250 being, respectively, the relative abundance and the trait value of the species  $k$  in the community  
251  $i$  and  $n_i$  being the number of species in the community  $i$ .

252 The complementarity effect on the traits was determined using the land equivalent ratio (LER);  
253 which is the relative area required for monoculture to grow with the same productivity as when  
254 the species are in mixture (Mead and Willey 1980). The LER was calculated for each species  
255 trait in the multi-specific plots as follows:

$$256 \quad LER = pLER_A + pLER_B = \frac{T_{A,multi-specific}}{T_{A,monospecific}} + \frac{T_{B,multi-specific}}{T_{B,monospecific}} \quad (4)$$

257 with  $pLER_A$  and  $pLER_B$  being the partial LERs for the species A and B;  $T_{A,multi-specific}$  and  
258  $T_{B,multi-specific}$  being the trait values of the species A and B in the multi-specific conditions; and  
259  $T_{A,monospecific}$  and  $T_{B,monospecific}$  being the trait values of the species A and B in their respective  
260 monospecific conditions. If  $LER > 1$ , the multi-specific condition presents an advantage for the  
261 trait value compared when the species is in monospecific condition. In the contrary, if  $LER <$   
262  $1$ , there is a detrimental effect on the trait of the multi-specific condition compare to the  
263 monospecific. The  $pLER$  allows to indicate competitive effects between the species, within the  
264 multi-specific condition, using  $pLER < (1/n)$  or  $pLER > (1/n)$  as an indices, with  $n$  the species  
265 number (Mead and Willey 1980; Hector 1998; Darch et al. 2018).

266

## 267 **Data analyses**

268 Comparison analyses highlighting the differences between the community-weighted traits of  
269 each tested condition were carried out using ANOVA and Tukey post-hoc tests on the  
270 community- weighted trait values of the three monospecific and the multi-specific conditions.

271 The effects of each vegetated condition in comparison to the control condition on the unit  
272 stream power and sediment retention were tested using Kruskal-Wallis and Dunn's tests.  
273 Comparative analyses using Mann-Whitney tests were performed on the USP and the sediments  
274 (quantities and granulometries) data, gathered under "monospecific" and "multi-specific"  
275 categories, in order to identify if there was a complementarity or a selection effect of the trait  
276 diversity on these processes.

277 To identify differences between the communities, ANOVA and Kruskal-Wallis analyses were  
278 computed accordingly to the normality of the data on the USP, the sediments (quantities and  
279 granulometries) and the LER data. The analyses' respective post-hoc tests Tukey and Dunn's  
280 were also performed. As the aim of the analyses was to understand the effects of the trait  
281 diversity on the tested variables, control data were excluded. All the statistical analyses were  
282 carried out using the "Stats" and "dunn.test" packages in the statistical software R (version  
283 3.3.2).

284

285

## 286 **Results**

### 287 **The traits in the monospecific conditions and their effects on the unit stream power and** 288 **sediment retention**

289 The comparison analyses of the trait values between each monospecific condition emphasised  
290 the contrasting leaf densities found between each species (Table 2). *C. pendula* presented  
291 significantly lower CW density-weighted projected stem area and CW density-weighted stem  
292 diameter with *F. arundinacea* and no difference with *T. vulgare* for the cited traits. The CW  
293 density-weighted leaf area of *C. pendula* was not different with *F. arundinacea* and larger than  
294 *T. vulgare*'s. The CW leaf area of *C. pendula* presented a significant difference with the leaf  
295 area of *F. arundinacea* and *T. vulgare*. Regarding the effects on the unit stream power and

296 sediment retention, the analyses showed no significant differences between the control and *T.*  
297 *vulgare*, while *C. pendula* and *F. arundinacea* had significant lower unit stream power and  
298 higher quantity of retained sediments than the control. *C. pendula* had higher hydraulic  
299 roughness (thus, a lower unit stream power) and quantity of sediments retained than *T. vulgare*.  
300

### 301 **Effects of the trait diversity on the community-weighted traits involved in the increase of** 302 **the hydraulic roughness and sediment retention**

303 The comparison analyses between the CW traits in the monospecific and the multi-specific  
304 conditions showed (1) a higher CW leaf area in the *C. pendula* monoculture than in the multi-  
305 specific condition; (2) more important CW leaf densities (0 – 5cm, 0 – 10cm and 0 – 20cm) in  
306 the multi-specific condition than in the *T. vulgare* monoculture; and (3) more important CW  
307 density-weighted leaf areas densities (0 – 5cm, 0 – 10cm and 0 – 20cm) in the multi-specific  
308 condition than in the *T. vulgare* monoculture (Table 2). Regarding the LER, the biomass  
309 productivity and the leaf density (0 – 5 cm; 0 – 10 cm and 0 – 20 cm) were higher in the multi-  
310 specific communities, with a LER > 1 (Table 3). The density-weighted projected stem area (0  
311 – 5 cm) and density-weighted stem diameter (0 – 5 cm) did not show differences between  
312 monospecific and multi-specific communities, with a LER = 1. Higher traits values were found  
313 for *F. arundinacea*, *C. pendula* (only the leaf area, the specific leaf area and the leaf density (0  
314 – 5 cm, 0 – 10 cm and 0 – 20 cm)) and *T. vulgare* (only the leaf density (0 – 5 cm, 0 – 10 cm  
315 and 0 – 20 cm)) in the multi-specific communities, with partial LER > 0.33. The biomass  
316 productivity was favoured in the multi-specific condition for *F. arundinacea* and *T. vulgare*  
317 (LER > 0.33) but was not higher for *C. pendula*.

318

### 319 **Trait diversity effects on the unit stream power, the sediment retention and the quantity** 320 **of each size category of sediment particle retained**

321 When averaging the three monospecific conditions under the category “monospecific”, the  
322 comparison analysis of the unit steam power showed no significant difference between the  
323 monospecific and the multi-specific conditions. There were no differences between the mean  
324 of the monospecific and the multi-specific conditions for the sediment quantities upstream,  
325 within and downstream the vegetation. Similar results were also found for the sediment particle  
326 sizes.

327 The comparison analysis between each condition regarding the unit stream power showed that  
328 *T. vulgare* had a significantly lower hydraulic roughness than *C. pendula* and the multi-specific  
329 condition (Fig. 4). Regarding the sediment retention (quantities upstream and within the  
330 vegetation), the results showed differences between the multi-specific condition and *T. vulgare*,  
331 which was also different from *C. pendula* (Fig. 5.A). When focussing on the size categories of  
332 the sediment particles retained by the vegetation, the multi-specific condition was not different  
333 from the monospecific conditions for each category; while *C. pendula* had a bigger amount of  
334 each size category than *T. vulgare* (Fig. 5.A). *F. arundinacea* did not present any difference  
335 with any of the other conditions for each sediment size fraction (Fig. 5.A). The quantity of  
336 particles between 100 and 2000  $\mu\text{m}$  showed no difference between each condition. The quantity  
337 of sediments downstream the vegetation was significantly higher for *T. vulgare* than for *C.*  
338 *pendula* and the multi-specific conditions (Fig. 5.B). The quantity of particles between 50 and  
339 100  $\mu\text{m}$  and between 100 and 2000  $\mu\text{m}$  was smaller for the multi-specific and *C. pendula* than  
340 for *T. vulgare* (Fig. 5.B).

341

342

## 343 **Discussion**

344 The aboveground traits of a vegetation constitute the main drivers for generating hydraulic  
345 roughness and sediment retention in an herbaceous community. The density-weighted leaf area



346 (product of the leaf area and the leaf density) influenced the hydraulic roughness and the  
347 sediment retention in the present study, highlighted by the lower values of this trait in the *T.*  
348 *vulgare* condition which showed the lowest hydraulic roughness and sediment retention. The  
349 density-weighted leaf area has been emphasised as a main trait influencing the hydraulic  
350 roughness, especially when combined with an important density-weighted stem diameter in  
351 herbaceous vegetation (Kervroëdan et al. 2018). This strong relationship between the density-  
352 weighted leaf area and the hydraulic roughness and sediment retention strengthen the  
353 hypothesis observed in the literature that vegetation composed of species with a good trade-off  
354 between leaf density and leaf area (i.e. presenting an important density of long leaves), such as  
355 graminoid species, would present a greater impact on the hydraulic roughness and a higher  
356 efficiency to retain sediments (Morgan 2004; Isselin-Nondedeu and Bédécarrats 2007). Better  
357 effects of the traits of graminoid species were also highlighted in the present study with a higher  
358 hydraulic roughness and sediment retention for *C. pendula* and *F. arundinacea* (with 84% and  
359 76.2% of the sediments retained, respectively) than *T. vulgare* (with 69.7% of the sediments  
360 being retained). The hypothesis that vegetation composed of traits inducing a high efficiency  
361 in sediment retention would present a wider diversity of sediment particle sizes was also  
362 emphasised in the graminoid conditions due to their higher density-weighted leaf area,  
363 especially for *C. pendula*. The effects of herbaceous vegetation, notably graminoid species, on  
364 sediment retention regarding the particle size fractions have been studied over the past decades,  
365 especially in the concern of pollutants dispersion with the finer particles (Meyer et al. 1995;  
366 Syversen and Borch 2005; Liu et al. 2008; Lambrechts et al. 2014). It has been shown that the  
367 coarser particles tend to deposit upstream the vegetation while finer one deposit within or pass  
368 through the vegetation. In our study, most of the particles coarser than 50  $\mu\text{m}$  were retained by  
369 all the conditions tested with vegetation while there was a decrease of the retention efficiency  
370 for finer particle sizes, which is the same pattern found in the literature (Meyer et al. 1995;

371 Syversen and Borch 2005). This was especially observed for *T. vulgare* (for particles <2 µm)  
372 which presented significantly lower density-weighted leaf areas and thus, a lower hydraulic  
373 roughness.

374 The effects of the trait diversity on runoff and soil erosion processes have been emphasised,  
375 with contentious results (Pohl et al. 2009; Martin et al. 2010; Erktan et al. 2013; Berendse et al.  
376 2015; Zhu et al. 2015). In this study, we focussed on the effects of the aggregation of contrasting  
377 traits involved in the increase of the hydraulic roughness and sediment retention which are  
378 negatively associated. We hypothesised that the aggregation of these contrasting traits would  
379 present a complementary effect on the hydraulic roughness and sediment retention, as well as  
380 would induce a greater quantity of sediment particle sizes retained by the vegetation. However,  
381 while the trait diversity should have led to a greater hydraulic roughness, the results showed no  
382 significant increase in hydraulic roughness nor sediment retention for the multi-specific  
383 communities. Indeed, the complementarity hypothesis stipulates that the trait divergence in  
384 plant communities influences ecosystem processes and leads to a more complete space and  
385 resources use (Loreau and Hector 2001). This absence of complementarity effects could not be  
386 explained by the biomass productivity of the plant community, as for a greater productivity in  
387 the multi-specific condition there was no greater effects on the hydraulic roughness nor on the  
388 sediment retention, emphasising that biomass productivity was not a major factor to increase  
389 sediment retention. The absence of differences between the mean of the monospecific and the  
390 multi-specific communities indicated a dominant effect of the traits of specific species in the  
391 community on runoff and sediment transport capacity (Grime 1998; Lorentzen et al. 2008).  
392 This dominance effect would be led by the traits of *F. arundinacea* and *C. pendula* and more  
393 specifically by their CW density-weighted leaf area, emphasising the greater effect of  
394 graminoid species. These results on dominance effects of the community-weighted traits are  
395 not in accordance with the complementarity effects of plant species diversity found on runoff,

396 soil erosion and soil aggregation capacity in other studies (Pohl et al. 2009; Martin et al. 2010;  
397 Zhang et al. 2015). However, these studies focussed on non-herbaceous spontaneous plant  
398 communities of mountainous or semi-arid environments, which usually comprise different (e.g.  
399 more intense) runoff and erosion episodes and adapted spontaneous vegetation towards these  
400 processes (Guerrero-Campo and Montserrat-Martí 2000). These opposing results could be  
401 explained by idiosyncratic effects (i.e. contrasting effects of the plant species diversity),  
402 impacted by species-traits and soil-plant interactions (Loreau 2000). The idiosyncratic effects  
403 could be influenced by the species combination and structure in the community (Parsons et al.  
404 1996; Loreau 2000; Erktan et al. 2013), which is consistent with results showing the decrease  
405 of soil erosion resistance with the disappearance of species in the community (Berendse et al.  
406 2015). Moreover, an increasing proportion of species with larger stems diameters would create  
407 preferential flow paths and further runoff intensity, which would impact the effect of the trait  
408 diversity on the hydraulic roughness and sediment retention (Parsons et al. 1996; Erktan et al.  
409 2013). This hypothesis is consistent with our results, showing the negative influence on the unit  
410 stream power of the traits of *T. vulgare* by reducing the hydraulic roughness and sediment  
411 retention within the multi-specific conditions, due to its larger stem diameters than the two  
412 other tested species. Negative effects of species with large stem diameters were also highlighted  
413 in the literature, highlighting their influence over the water path within the vegetation and the  
414 overall neutral effect of trait diversity (Erktan et al. 2013). This postulate coincides with the  
415 traits' effects found regarding the size of the sediment particles upstream the vegetation, as the  
416 preferential flow paths induced by the presence of larger stems would accelerate the flow  
417 velocity at the path's scale and further the transport of sediment particles. Indeed, while a wider  
418 variety of sediment particle sizes was expected within the retained sediments by the multi-  
419 specific condition, there was no significant difference between the monospecific and the multi-  
420 specific conditions for each particle size category. To understand the idiosyncratic effects on

421 hydraulic roughness and sediment retention, perspective is to examine the effects of trait  
422 diversity on hydraulic roughness and sediment retention by using a wide gradient of functional  
423 diversity, with a variation in the abundance of the traits involved in hydraulic roughness  
424 increase, to unravel the relationship between trait diversity and sediment retention.

425

426

## 427 **Conclusions**

428 This trait-based ecohydrology study allowed to further the understanding of the effect of trait  
429 diversity on runoff and soil erosion processes. The results emphasised that there was not a better  
430 effect of trait diversity on the hydraulic roughness and sediment retention, as well as on the  
431 quantity of sediment fractions. The absence of negative effects on sediment retention suggests  
432 that multi-specific communities can be used to mitigate soil erosion and can be recommended  
433 because plant species and functional diversity could offer other ecosystem processes and  
434 services. Perspective is to examine the effects of functional diversity on several main ecosystem  
435 processes in herbaceous hedges created to mitigate soil erosion, to design multi-functional  
436 ecosystems.

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438

## 439 **Authors' Contributions**

440 Léa Kervroëdan, Michel-Pierre Faucon and Romain Armand conceived the objectives and  
441 designed the methodology; Léa Kervroëdan and Mathieu Saunier collected the data; Léa  
442 Kervroëdan analysed the data; Léa Kervroëdan and Michel-Pierre Faucon led the writing of the  
443 manuscript. All authors contributed critically to the drafts and gave final approval for  
444 publication.

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597 **Fig. 1 Experimental plots with three monospecific and one multi-specific communities.**

598 The photos from October 2016 were taken just after the plantation and the ones from September  
599 2017 were taken a month *prior* experiment.

600

601 **Fig. 2 Experimental site. A – Location of the experimental site in Drosay, France and B**  
602 **– Arrangement of the plots within the experimental area.**

603

604 **Fig. 3 Runoff simulator used for the experiments.**

605

606 **Fig. 4 Differences between each community for the unit stream power.** The bars represent  
607 the mean  $\pm$  standard error. The letters represent the significant differences between each  
608 condition according to Tukey post-hoc tests. The significance level “ns” means not significant.

609

610 **Fig. 5 Differences between each community for (A) the sediment quantities for each**  
611 **particle size category upstream the vegetation and (B) the sediment quantities for each**  
612 **particle size category downstream the vegetation.** The error bars represent the mean  $\pm$   
613 standard error. The letters represent the significant differences between each condition  
614 according to the Tukey post-hoc tests, for each sediment size fraction. The significance level  
615 “ns” means not significant. The uppercase letters in bold represent the differences between each  
616 condition in the overall sediment quantities, according to the Tukey post-hoc tests.