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1 **Trait-based sediment retention and runoff control by herbaceous vegetation in**
2 **agricultural catchments. A review**

3

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12

13

14 **Abstract**

15 Soil degradation by concentrated runoff and soil erosion induces major environmental and
16 economic damages, notably in agricultural areas under temperate climates. The use of
17 herbaceous vegetation aims to increase the hydraulic resistance and thus reduce runoff and soil
18 erosion while retaining sediments on site. However, the identification of the most suitable
19 species to mitigate runoff is often specific to a phytogeographical territory and hampered by
20 the intraspecific variability, which reduces the transposition of a solution to other territories
21 and the ability to quantify the effects of the vegetation. Using a plant trait-based approach
22 allows understanding and characterising the direct effects of the vegetation on runoff and soil
23 erosion mitigation as well as on the sediment retention increase. Here, we review the influence
24 of plant aboveground functional types and traits of herbaceous vegetation on the hydraulic
25 resistance and sediment retention and the contentious effects of the functional diversity on the

26 hydraulic resistance and sediment retention, within agricultural catchments. Using this
27 knowledge, we propose applications of the trait-based approach to design and manage
28 herbaceous hedges for sediment retention and soil erosion control. This review synthesises
29 recent advances regarding the effects of the functional traits on runoff and sediment retention
30 and defines a trait-based selection method of the plant species for runoff and soil erosion
31 control.

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33

34 **Keywords:** Agroecological engineering; herbaceous hedges; hydraulic resistance; plant
35 functional traits; plant-soil interactions; runoff-plant interactions.

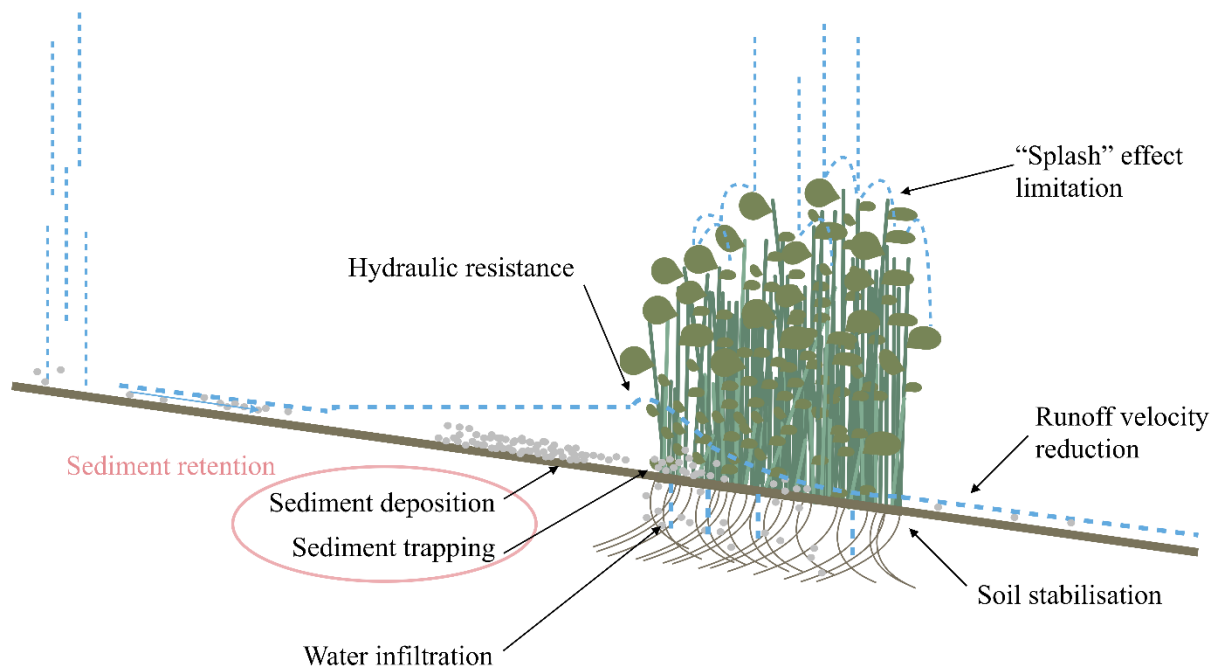
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38 **1. Introduction**

39 Soil erosion by water is a natural hazard frequently observed in tropical, Mediterranean and
40 temperate areas leading to soil degradation, and is accentuated by anthropogenic factors,
41 especially by agriculture (Poesen, 2018). The efficiency of herbaceous vegetation to mitigate
42 soil erosion has been established for the past decades and their different effects on the soil
43 erosion processes (Figure 1) have been intensively studied (Haan *et al.*, 1994; Liu *et al.*, 2020;
44 Ludwig *et al.*, 2005; Mekonnen *et al.*, 2015). Herbaceous vegetation reduce soil erosion by
45 protecting the soil against the raindrops impacts; furthering infiltration; stabilising soil;
46 increasing surface roughness; reducing runoff velocity; boosting evapo-transpiration; and
47 inducing sediment retention (Morgan, 2009; Styczen & Morgan, 1995). However, the plants
48 efficiency towards runoff and soil erosion reduction depends on the species used, which points
49 to the importance of inter and intraspecific variations in plant traits (Cao *et al.*, 2015; Hayes *et*
50 *al.*, 1984). The effects of plant root density, length density, tensile strength, area ratio and

51 system morphology on soil and slope stabilisation as well as on soil shear strength have been
52 thoroughly analysed (De Baets *et al.*, 2006, 2009; Stokes, 2007; Stokes *et al.*, 2014). The
53 reduction of the splash-driven soil detachment due to the vegetation has also been well
54 documented, showing the positive effect of the plant canopy on the decrease of the raindrop
55 kinetic energy (Gyssels *et al.*, 2005; Morgan, 2004; Styczen & Morgan, 1995). The infiltration
56 rate and the hydraulic resistance are the two main processes inducing sediment retention at the
57 vegetation patch scale. As long as the hydraulic conductivity of the soil remains unsaturated,
58 the soil infiltration rate, increased by the presence of the vegetation, slows the runoff generation
59 (Styczen & Morgan, 1995). However, once the soil reaches the saturated hydraulic
60 conductivity, the main process inducing sediment retention and the reduction of the runoff flow
61 velocity is the hydraulic resistance created by the vegetation (Styczen & Morgan, 1995), which
62 also furthers infiltration (Dabney *et al.*, 1995; Dosskey *et al.*, 2010; Gilley *et al.*, 2000). The
63 hydraulic resistance is the force that overland flow experiences on the soil surface and which
64 may be influenced by the frictional drag-over the elements present at the soil surface scale such
65 as residue cover, clods, gravel and standing vegetation (Gilley & Kottwitz, 1995). Indeed, the
66 aboveground biomass of the herbaceous vegetation slows the flow velocity down, creating a
67 backwater area in front of the vegetation where sediments settle as the sediment transport
68 capacity of the flow is reduced (Akram *et al.*, 2014; Cantalice *et al.*, 2015; Hussein *et al.*, 2007).
69 This plant effect can be modelled by the use of hydraulic roughness coefficients, such as Darcy-
70 Weisbach f and the Manning's n (Haan *et al.*, 1994). Most of the studies referencing the
71 reduction of soil erosion by plants focussed on semi-arid and Mediterranean climates, as higher
72 soil erosion rates are found in these areas (De Baets *et al.*, 2009; Durán Zuazo & Rodríguez
73 Pleguezuelo, 2008; Liu *et al.*, 2020; Vannoppen *et al.*, 2015; Zhu *et al.*, 2015), giving soil
74 erosion processes under temperate climates less importance, mainly due to the average slope
75 gradients lower than 5% (Remy & Le Bissonnais, 1998).



76

77 **Figure 1. Effects of herbaceous vegetation on soil erosion processes**

78

79 The reduction of the runoff flow velocity and soil erosion rates is mainly induced by the
 80 hydraulic resistance of the plants at the vegetation patch scale in temperate agricultural
 81 catchments. Distinctive to temperate oceanic climates, these catchments are regularly affected
 82 by intense runoff and soil erosion episodes, due to the intensified tillage and the cultivation of
 83 annual crops on sloping loamy soils (Boardman & Poesen, 2006; Gobin *et al.*, 2003; Styczen
 84 & Morgan, 1995). The improvement of the herbaceous vegetation efficiency for the mitigation
 85 of soil erosion requires a good understanding of the relationship between the plant aboveground
 86 functional traits and the hydraulic resistance. Functional traits are defined as “morpho-physio-
 87 phenological traits which indirectly impact fitness via their effects on growth, reproduction and
 88 survival” (Violle *et al.*, 2007). Trait-based ecology and agroecology allow characterising the
 89 plant responses to environmental changes and their effects on ecosystem processes, such as
 90 soil erosion, and allow the transposition of these effects to other biogeographical territories
 91 (Burylo *et al.*, 2012; Kervroëdan *et al.*, 2018; Liu *et al.*, 2018b). Studying the linkages between
 92 the plant functional traits and the soil properties and processes constitutes an essential approach

93 to understand hydrological processes allowing to design new ecosystems offering the best
94 efficiency for the reduction of soil erosion (Faucon *et al.*, 2017). The functional diversity,
95 defined as “the value, range, and relative abundance of plant functional traits in a given
96 ecosystem” (Díaz *et al.*, 2007a; Tilman, 2001), influences the ecosystem processes and
97 functioning, although its effects are contentious (Garnier *et al.*, 2016). The “mass ratio
98 hypothesis” stipulates that the ecosystem properties are driven by the traits of the dominant
99 species in the community (Grime, 1998). Accordingly, the ecosystem properties would be
100 determined by the community-weighted mean trait values of the dominant species (Díaz *et al.*,
101 2007b). On the other hand, the ecosystem processes can also be driven by non-additive effects
102 (i.e. complementarity or facilitation) among the coexisting species with diverse trait values,
103 which can be designated by functional diversity indices (e.g. functional divergence, distance
104 between high abundant species and the centre of the functional space) (Díaz *et al.*, 2007b;
105 Garnier & Navas, 2012; Mouillot *et al.*, 2011). Given that functional diversity impacts various
106 ecological processes and notably soil erosion (Erktan *et al.*, 2013; Garnier *et al.*, 2016; Zhu *et al.*,
107 2015), the effects of the plant functional diversity can be analysed to understand the
108 potential impacts on the hydraulic resistance and the resulting sediment retention.

109 Even though a number of studies have reviewed the effects of vegetation on the soil erosion
110 processes, linking plants with the overall soil erosion rates and soil loss, only a limited
111 specification of the plant traits influencing more targeted processes, such as sediment retention,
112 have been reported (Gyssels *et al.*, 2005; Liu *et al.*, 2018; Puigdefábregas, 2005). Identifying
113 the efficient functional traits to reduce concentrated runoff and soil erosion would allow
114 selecting plant species and designing herbaceous infrastructures to go further into land planning
115 and soil protection. This review synthesises the recent advances and contemporary
116 understanding on the effects of the plant functional traits in herbaceous vegetation on runoff
117 mitigation, sediment retention and soil erosion control in agricultural catchments by reviewing:

118 (1) the influence of plant aboveground functional types and traits on the hydraulic resistance
119 and sediment retention; (2) the contentious effects of the functional diversity on the hydraulic
120 resistance and sediment retention and (3) the applications of the trait-based approach for the
121 design and the management of herbaceous hedges for sediment retention and erosion control.

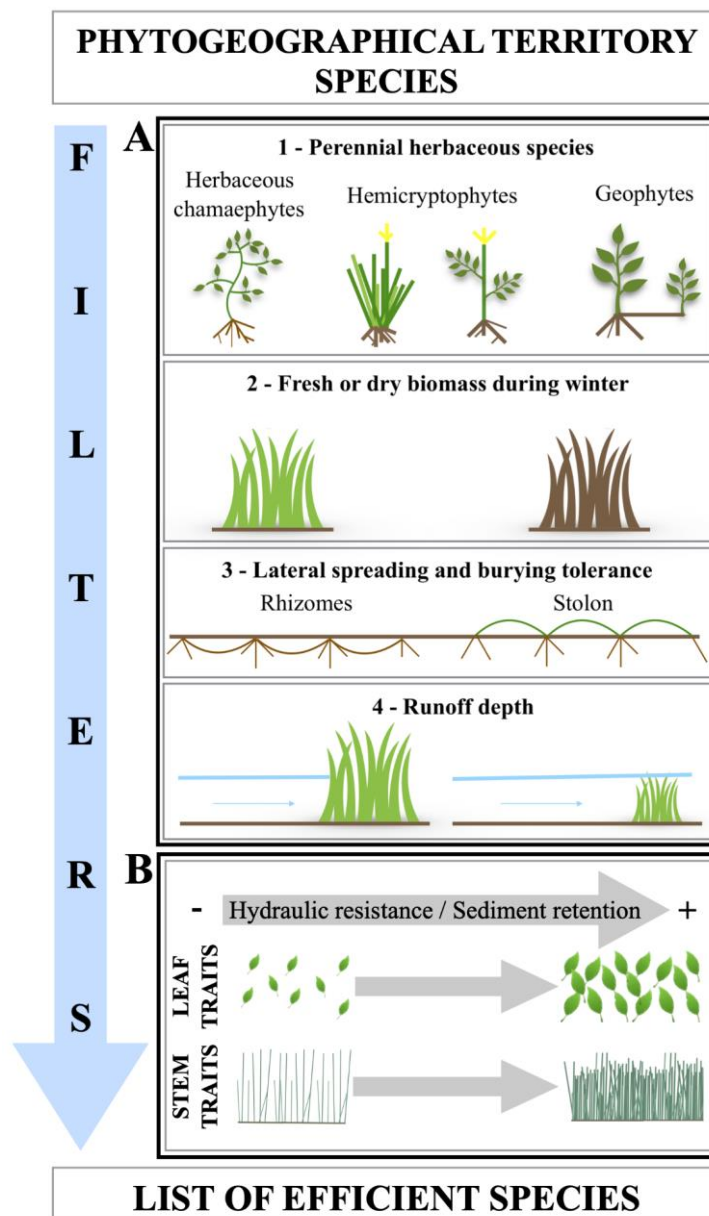
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123 **2. Effects of plant aboveground functional types and traits on the hydraulic** 124 **resistance and sediment retention**

125 2.1. Effects of the plant functional types

126 The characterisation of the functional types influencing the hydraulic resistance is required to
127 identify the most relevant herbaceous vegetation (Figure 2A). Species favouring vegetative
128 spreading with rhizomes, tillers or stolon can play a key role in the increase of the hydraulic
129 resistance and sediment retention. Indeed, rhizomes and stolon guarantee a lateral spreading
130 growth pattern, with a dense and homogenous ground cover (100%) limiting the presence of
131 preferential flow paths within the vegetation, and a burying tolerance towards recurring
132 sedimentation (Maun, 1998). The perennial herbaceous species under the Raunkiaer's life-form
133 categories "herbaceous chamaephytes" and "hemicryptophytes" provide an effective soil cover
134 through all seasons by increasing the hydraulic resistance in comparison to bare soils (Bautista
135 *et al.*, 2007; Berendse *et al.*, 2015; Martin *et al.*, 2010). Within these life-form categories, the
136 caespitose and non-caespitose types with fresh or dry biomass in winter allow a constant
137 ground cover when soil erosion is observed at its highest in cultivated areas under temperate
138 climates (Boardman & Poesen, 2006; Durán Zuazo & Rodríguez Pleguezuelo, 2008). The
139 herbaceous vegetation should present a higher vegetative height than the water maximal level
140 found in the targeted areas of implantation (e.g. 20cm in north-west Europe at a frequency of
141 5 to 10 years in a catchment of 20ha (Richet *et al.*, 2017)) to be efficient against concentrated
142 flows (Dillaha *et al.*, 1989; Van Dijk *et al.*, 1996). Water maximal level should be estimated

143 using the discharges of the erosional episodes against which the herbaceous vegetation should
 144 be efficient. The functional types involved in the increase of the hydraulic resistance and
 145 sediment retention could constitute a set of criteria to select potential candidate species within
 146 a specific phyto-geographical area for soil erosion control (Figure 2A). Perspective is to define
 147 the selection method and to integrate the effects of functional traits into the selection process
 148 to design efficient herbaceous vegetation to mitigate soil erosion.



149
 150 **Figure 2. Functional types (a) and traits (b) involved in the increase of the hydraulic resistance and sediment**
 151 **retention under temperate climates to select efficient herbaceous vegetation**

152

2.2. Effects of leaf and stem functional traits

153 Most of the studies about the effects of vegetation on soil erosion and sediment retention focus
154 on the impacts of the aboveground functional traits. Both stem and leaf traits have been
155 identified for the past decades as efficient for triggering sediment retention (Figure 2B). The
156 leaf density and area are the main leaf traits impacting sediment retention (Burylo *et al.*, 2012;
157 Graff *et al.*, 2005; Lambrechts *et al.*, 2014) and the hydraulic resistance (Kervroëdan *et al.*,
158 2018). The stem density and diameter are two of the main stem traits influencing sediment
159 retention (Bochet *et al.*, 2000; Isselin-Nondedeu & Bédécarrats, 2007; Mekonnen *et al.*, 2016;
160 Meyer *et al.*, 1995; Morgan & Duzant, 2008). The efficiency of the stem density on runoff
161 depends on the slope and the type of soil. Indeed, on 20% slopes of silty soils, vegetation with
162 a stem density of 7500 stems.m⁻² would reduce the flow velocity by 90.6%, while on a 10%
163 slope 2500 stems.m⁻² would reduce the velocity by 91.9%, in comparison to bare soil (Morgan,
164 2004). Focussing on the effects of traits on the hydraulic resistance at the vegetation scale in
165 north-west Europe, Kervroëdan *et al.* (2018) investigated the effects of density-weighted traits
166 (trait weighted by the density of the trait). This approach identified the most efficient
167 combinations of density-weighted traits as: (1) the density-weighted leaf area (i.e. leaf area x
168 leaf density, in mm².dm⁻²) with the density-weighted stem diameter (i.e. stem diameter x stem
169 density, in mm.dm⁻²) and (2) the density-weighted leaf area with the density-weighted
170 projected stem area (which represents the projected area towards the flow; stem projected area
171 x stem density, in mm².dm⁻²), also emphasising the indirect effect of the stem density. The stem
172 stiffness has also been found to induce sediment retention (Meyer *et al.*, 1995), although
173 contrasting results are found in the literature (Burylo *et al.*, 2012). These contrasting results
174 could be explained by the differences in the discharges used: with higher discharges (from 11
175 to 43.7 l.s⁻¹.m⁻¹) an effect of the stem stiffness was found compared to smaller discharges (1.6
176 l.s⁻¹.m⁻¹); indicating that the effects of traits could change depending on the discharge. Indeed,

177 the leaf area was found efficient for small discharges (2 and 4 L.s⁻¹.m⁻¹) while the leaf density
178 only had an effect at higher discharges (8 and 11 L.s⁻¹.m⁻¹) (Burylo *et al.*, 2012; Kervroëdan *et*
179 *al.*, 2018). A changing response of the leaf structure, stem density and diameter on the hydraulic
180 resistance and sediment retention was also found depending on the discharge used. At low
181 discharges, the hydraulic resistance was dependent on the vegetation density (Temple *et al.*,
182 1987; Van Dijk *et al.*, 1996); while at higher discharges, with flow depths higher than the
183 deflecting vegetation height, the hydraulic resistance was found primarily influenced by the
184 stem density, diameter and stiffness, and less by the leaf structure (Meyer *et al.*, 1995; Temple
185 *et al.*, 1987; Vieira & Dabney, 2012).

186 The knowledge of the effects of plant traits on runoff and sediment retention constitutes an
187 advancement for the modelling of the vegetation effects on soil erosion and runoff mitigation,
188 such as in VFSSMOD (Vegetative Filter Strip Modelling System). This model evaluates the
189 effects of vegetation on hydrology and sediment transport processes through vegetative filter
190 strips. The model is physically based and simulates the sediment retention resulting of the
191 vegetation hydraulic resistance (e.g. Manning index). Although this model is widely used, the
192 characterisation of the hydraulic resistance of the vegetation is based on a limited number of
193 plant traits: stem density and height (Muñoz Carpena & Parsons, 2014). Adding traits identified
194 as efficient in increasing the hydraulic resistance in herbaceous hedges would extend the
195 precision of the modelling of the efficiency of vegetative barriers and would broaden the field
196 of application of the model. Therefore, improvements may apply to: (1) the estimation of the
197 sediment transport and retention capacities, (2) the application of the model for other vegetative
198 objects than vegetative filter strips and (3) the design of herbaceous vegetation by creating
199 efficient vegetation for the hydraulic processes encountered in the implantation landscape.
200 Perspective is to compare results obtained using the model with ones obtained by

201 experimentations and to identify the main traits increasing the hydraulic resistance and
202 sediment retention.

203

204

205 2.3.Contentious effects of the functional diversity in herbaceous vegetation on
206 the hydraulic resistance and sediment retention

207 For decades, studies highly focused on the effects of the functional diversity on few main
208 ecosystem processes, notably related to the carbon cycles (Cadotte, 2017; Garnier *et al.*, 2004;
209 Zuo *et al.*, 2016), but the effects of the functional diversity for a same process are found
210 contrasting (Faucon *et al.*, 2017; Garnier *et al.*, 2016; Mariotte *et al.*, 2017). These contentious
211 results stress the need to widen the range of processes related to plant-soil interactions which
212 could be affected by the functional diversity.

213 Regarding runoff and soil erosion processes, most of the studies used a taxonomical
214 characterisation of the communities to analyse the effects of plant diversity (Bautista *et al.*,
215 2007; Berendse *et al.*, 2015; Fullen, 1998; Hou *et al.*, 2016; Martin *et al.*, 2010; Meyer *et al.*,
216 1995; Pohl *et al.*, 2009; Turnbull *et al.*, 2008; Zhang *et al.*, 2015). A number of these studies
217 focussed on the effects of non-herbaceous plant roots on soil stabilisation and vegetation patch
218 pattern impact on erosion rates, showing that an increase of diversity led to a better soil
219 resistance and stabilisation (Balvanera *et al.*, 2006; Gyssels *et al.*, 2005), as well as an increase
220 of sediment retention in heterogeneous vegetation patterns (Hou *et al.*, 2016). Other studies
221 focused on the effects of functional groups, marking a first step into the use of a functional
222 characterisation of the vegetation effects on runoff and soil erosion processes. The results
223 showed complementarity effects on runoff, soil erosion and soil aggregation capacity (Martin
224 *et al.*, 2010; Pohl *et al.*, 2009; Zhang *et al.*, 2015). However, using functional diversity – by
225 taking into account the aspects of diversity that impact the community structure and functions

226 – was highlighted to be a better predictor to characterise the effects of plant diversity on
227 ecosystem processes (Cadotte *et al.*, 2011), such as runoff and soil erosion.

228 Land restoration using monospecific vegetation may be inefficient in reducing soil erosion
229 given their simple canopy (Cao, 2011; Cao *et al.*, 2009), however the effects of functional
230 diversity on runoff and soil erosion processes have not been thoroughly studied. It is
231 hypothesised that vegetation with high species and functional diversity positively influence the
232 hydraulic resistance and reduce soil erosion. Plants with wider stem diameters would support
233 the stems and leaves of species with higher leaf area and density. The biomass productivity of
234 herbaceous vegetation positively influences the hydraulic resistance and sediment retention
235 (Burylo *et al.*, 2012; Podwojewski *et al.*, 2011). Positive effects of the functional diversity on
236 plant productivity would thus lead to an increase of the hydraulic resistance and sediment
237 retention. These positive effects could notably come from the belowground traits by inducing
238 a diversification in the nutrients and water sources accessibility and acquisition in the soil
239 profile (Faucon *et al.*, 2017; Tilman *et al.*, 2014). Only few studies have focussed on the
240 functional diversity effects on soil erosion at the ecosystem level, with controversial results
241 (Erktan *et al.*, 2013; Kervroëdan *et al.*, 2019; Zhu *et al.*, 2015). In semi-arid grasslands, the
242 functional divergence explained up to 40% of the variation of the erosion rates, due to a greater
243 niche differentiation within the tested communities (Zhu *et al.* 2015). However, when focusing
244 on the effects of functional types mixtures in Mediterranean mountainous ecosystems, no effect
245 of the functional diversity on sediment retention was found, due to areas of least resistance to
246 flow created by the shrubs and trees individuals (Erktan *et al.*, 2013). These results are
247 consistent with other observed on the effect of trait divergence on the hydraulic resistance and
248 sediment retention for herbaceous vegetation in a temperate agricultural catchment
249 (Kervroëdan *et al.*, 2019). However, the number of studies is limited to fully understand the
250 effects of functional diversity on the hydraulic resistance and sediment retention. Perspective

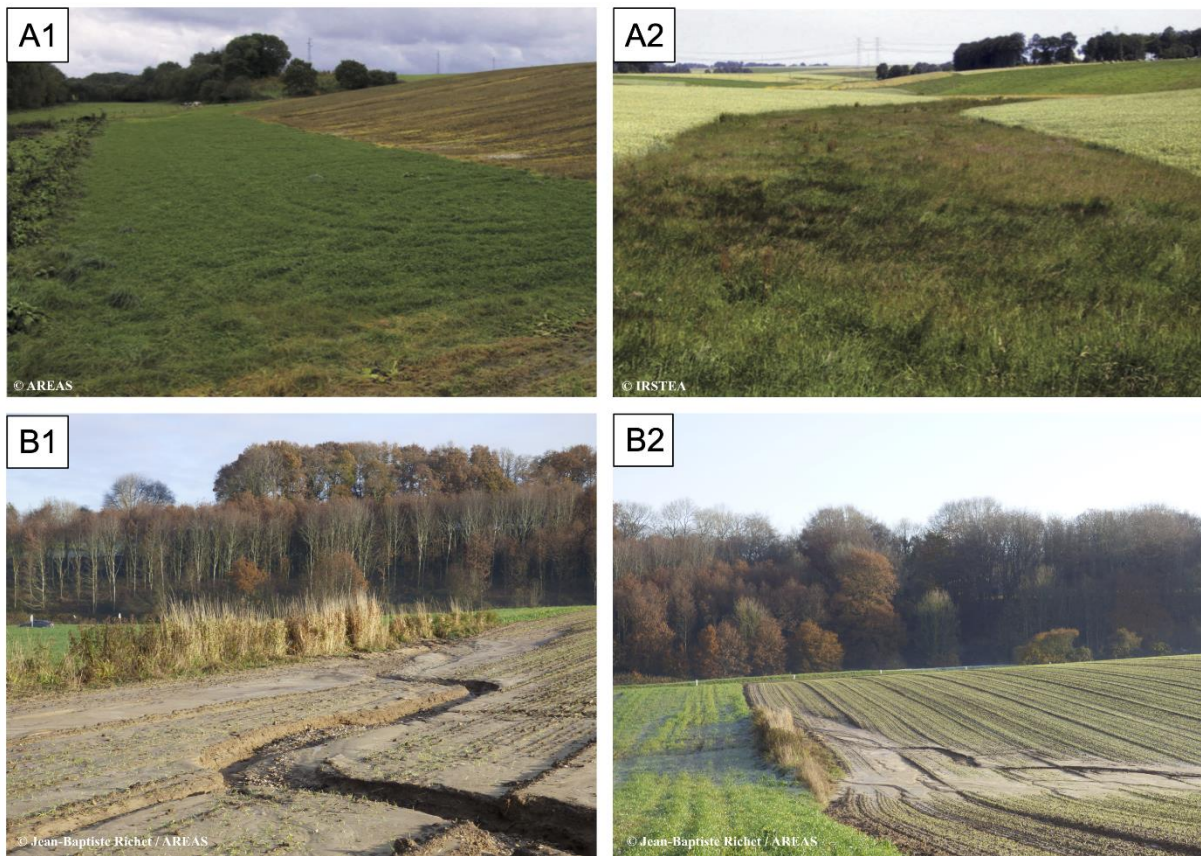
251 is to study a number of combinations of species and a wide gradient of functional diversity
252 comprising traits involved in the hydraulic resistance and sediment retention increase. This
253 would allow analysing the contentious findings and identifying if they could be the result of
254 idiosyncratic effects of the traits, corresponding to contrasting effects of the functional diversity
255 influenced by the species-traits and the plant-soil interactions.

256

257

258 **3. Applications to design and manage herbaceous hedges for sediment retention and** 259 **soil erosion control**

260 In agricultural areas, implanting vegetative barriers in the form of herbaceous hedges across
261 the flow path would reduce sheet and concentrated erosion, as well as retaining sediment
262 (Dabney *et al.*, 1995). Herbaceous hedges are narrow strips of dense and stiff perennial
263 vegetation and present a high efficiency in reducing soil erosion caused by concentrated flows
264 and for sediment retention (Dabney *et al.*, 1995; Yuan *et al.*, 2009). They have been used for
265 decades in various areas such as in the United States, tropical or semi-arid areas (Dabney *et al.*,
266 1995; Gilley *et al.*, 2000; Liu *et al.*, 2018; Mekonnen *et al.*, 2016; Meyer *et al.*, 1995; Wu *et al.*,
267 2010; Xiao *et al.*, 2012). They are differentiated from vegetative filter strips by their width and
268 functions (Figure 3). While herbaceous hedges are specifically designed to further the hydraulic
269 resistance and sediment retention in concentrated flow paths, vegetative filter strips further the
270 water infiltration and sediment retention within a wide area (> 5m width) under superficial and
271 shallow flows and are useless under concentrated runoff events (Dabney *et al.*, 1995; Dillaha
272 *et al.*, 1989).



273

274 **Figure 3. Comparison between vegetative filter strips (a) along: 1—the thalweg's bottom line and 2—an**
 275 **agricultural field; and a multi-specific herbaceous hedge (b) between two fields across a concentrated flow**
 276 **(1 and 2)**

277

278 3.1.Candidates plant species to design herbaceous hedges: the case of north-
 279 west Europe

280 The first challenge is to apply defined criteria to select the species composition of herbaceous
 281 hedges in different phyto-geographical territories. Focussing on north-west Europe, composed
 282 of 3,500 spermatophyte species (Lambinon *et al.*, 2012), with the following criteria based from
 283 the functional types: (1) perennial herbaceous vegetation “herbaceous chamaephytes” and
 284 “hemicryptophytes” which present biomass in winter (fresh or dry biomass) when soil erosion
 285 is observed at its highest in north-west Europe (Boardman & Poesen, 2006); (2) the presence
 286 of rhizomes or stolon; (3) a minimum vegetative height equal or higher than 20 cm, as it is the

287 maximal level of the water flows in the north-west European catchments; (4) a broad ecological
288 niche for an implantation in a wide range of silty agricultural soils; and (5) non-weed species
289 to avoid the spreading of the vegetation into the agricultural fields; only 76 candidate species
290 potentially able to mitigate runoff and soil erosion are highlighted (Table 1; Villarroel, 2015).
291 The characterisation of the effects of leaf and stem traits on the hydraulic resistance and
292 sediment retention should be integrated into the selection criteria to narrow the list to efficient
293 species, using the range of efficiency of the trait values. The threshold values of traits from
294 which plants would efficiently increase the hydraulic resistance and sediment retention were
295 identified using the unit stream power critical value of $0.004 \text{ m}\cdot\text{s}^{-1}$ (Govers, 1990), being the
296 identified value of unit stream power from which the soil is likely to erode (for bare loess soils
297 (D_{50} from $58 \mu\text{m}$ to $218 \mu\text{m}$), with slopes ranging from 1° to 8° for discharges between 2 and
298 $100 \text{ cm}^3\cdot\text{cm}^{-1}\cdot\text{s}^{-1}$ (0.2 to $10 \text{ l}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$). These data were extracted from data in Kervroëdan et al.
299 (2018), as it focussed on the effects of traits on the hydraulic resistance in agricultural
300 catchments from north-west Europe (Table 2). By using both the efficient combinations and
301 the identified threshold values, the 76-species list of potential candidate species could be
302 narrowed down to the most interesting ones to create herbaceous hedges in north-west Europe.
303 Perspective is to select the candidate species for north-west Europe and other
304 phytogeographical territories regarding their stem and leaf traits using studies identifying the
305 minimal threshold values of traits for the processes occurring in different phytogeographical
306 territories. Trait databases could also be used to select the candidate species and could be
307 completed, as there are many traits of interest for runoff and soil erosion mitigation that are
308 lacking for many species.

309

310

3.2. Monospecific or multi-specific herbaceous hedges?

311 Biodiversity usually corresponds to a more ecologically stable system, as a stable and healthy
312 system would be less vulnerable to abiotic and biotic stress (Tilman, 1999). Therefore,
313 practitioners may ask if it is better to use only one or a few species that can efficiently increase
314 sediment retention and mitigate runoff and soil erosion, or if a diverse range of species,
315 sometimes less efficient, should be used. Most of the studied herbaceous hedges through the
316 literature were monospecific hedges (Cao et al., 2015; Cullum et al., 2007; Dabney et al., 2004;
317 Huang et al., 2010; Hussein et al., 2007; Lin et al., 2009; Liu et al., 2018; Mekonnen et al.,
318 2016; Meyer et al., 1995). However, the use of multi-specific vegetation to control runoff and
319 soil erosion has been studied (Bautista *et al.*, 2007; Berendse *et al.*, 2015; Erktan *et al.*, 2013;
320 Hou *et al.*, 2016; Kervroëdan *et al.*, 2019; Martin *et al.*, 2010; Pohl *et al.*, 2009; Turnbull *et al.*,
321 2008; Zhang *et al.*, 2015; Zhu *et al.*, 2015), but some of the studies focussed on the diversity
322 of different functional types or within vegetation patches. A positive effect of plant diversity
323 was also found on the soil erosion resistance (Berendse *et al.*, 2015). Trait divergence showed
324 positive effects on sediment retention and the hydraulic resistance in herbaceous vegetation in
325 loamy agricultural catchments, although the efficiency of the multi-specific vegetation could
326 be lowered by the presence of species with large stem (Kervroëdan *et al.*, 2019).

327 Taking into account these contentious results and that species diversity within herbaceous
328 hedges did not show negative interactions with the efficiency of the multi-specific hedges, it
329 can be suggested using only few species with the best traits involved in decreasing runoff,
330 increasing sediment retention and mitigating soil erosion in a same herbaceous hedge (Rey &
331 Labonne, 2015). However, species diversity should be favoured as much as possible to:
332 (1) enable reducing the risks of failure of vegetation systems in the case of the loss of a species
333 on a site due to abiotic/biotic factors ((Berendse *et al.*, 2015; Doak *et al.*, 1998), and (2) provide
334 other ecosystem services (e.g. habitat creation, ecological connectivity enhancement,
335 integrated pest control).

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3.3. Management of the herbaceous hedges to maintain their efficiency for sediment retention and erosion control

Once the herbaceous hedges are designed and implanted, definition of their management plan is essential to maintain or improve their efficiency on the hydraulic resistance, sediment retention and erosion control. To do so, it is necessary to preserve the initial vegetation structure, which has the best community-weighted traits involved in the increase of the hydraulic resistance for processes in north-west Europe (i.e. leaf area and density, density-weighted leaf area, stem projected area and stem diameter), by slowing down the vegetation succession and, notably, shrub and tree colonisation. The establishment of scattered trees or shrubs into the herbaceous hedge would enhance its infiltration capacity (Christen and Dalgaard 2013), as long as they are kept at a low height and present a light foliage to avoid competition and the reduction of the development of herbaceous species. The presence of too many ligneous species would limit the development of the herbaceous species by competing for the light and would then lead to the degradation of the herbaceous vegetation and thus, limit the effects on the hydraulic resistance and sediment retention. Cutting the vegetation is recommended in order to limit the dominance of tree and shrub species over herbaceous species within the hedge. Cutting the hedge should be performed every two/three years at the end of spring (circa end of June) in order to (1) allow the plants to grow back before the highest erosion events in winter and (2) limit the damages on the local fauna which use the herbaceous hedges to nest. The first 10 cm should be left as a cover to ensure a minimum survival of the plant in case an erosive event happens before the regrowth of the plants. Perspective is to test these management practices regarding the durability of the herbaceous hedge and its efficiency towards sediment retention.

361 3.4. From plot to catchment: location design and modelling of herbaceous
362 hedges using a trait-based approach

363 Numerous soil and landscape processes can control runoff sources and pathways, which results
364 in a spatially heterogeneous runoff and erosion distribution (Vandaele & Poesen, 1995).
365 Sediment control is site specific and thus requires specific studies to target the efficiency of the
366 herbaceous hedges (Mekonnen *et al.*, 2015; Tomer *et al.*, 2008). The first criteria to take into
367 account when designing herbaceous hedges is setting the expected levels of impacts, regarding
368 the rainfall properties and the reduction of suspended sediments. As the effects of the functional
369 traits can change regarding the flow characteristics (i.e. discharges), it is important to
370 implement the desired efficiency range of the hedge depending on the flow discharges into its
371 design (Kervroëdan *et al.*, 2018). For recurrent processes (from twice to once a year), the
372 vegetation composing the hedge should comprise dense stems with large diameters, as well as
373 large leaf areas. For more stronger processes occurring less regularly (from once every two to
374 five years), vegetation with dense leaves and stems, important leaf areas and large stem
375 diameters should be considered for the design of herbaceous hedges. The following factors
376 should also be taken into account for design and modelling purposes (Carluer *et al.*, 2017;
377 Dosskey *et al.*, 2015): (1) the specific catchment area (i.e. upslope area contributing to runoff
378 generation); (2) the soil characteristics (e.g. texture); (3) the slope gradient and topographical
379 features (e.g. thalwegs); (4) the crops and (5) the observed runoff pathways. These factors can
380 be implemented in a scoping tool to help local planners to set-up the herbaceous hedges at the
381 most efficient location (Carluer *et al.*, 2017; Dosskey *et al.*, 2011, 2015; Tomer *et al.*, 2008).
382 These tools often rely on modelling soil erosion and runoff pathways using field scale (e.g.
383 VFSMOD, CREAMS, TRAVA, WEPP) or catchment scale (e.g. LISEM, GeoWEPP, SWAT)
384 models (Arnold *et al.*, 2012; de Roo *et al.*, 1998; Deletic, 2001; Flanagan *et al.*, 2001; Knisel
385 & Nicks, 1980; Muñoz Carpena & Parsons, 2014; Renschler *et al.*, 2002). Methods to optimise

386 the location of vegetated objects such as filter strips have been developed (Gumiere *et al.*,
387 2011); however, herbaceous hedges functioning differently than filter strips, characterising a
388 protocol to locate suitable areas for herbaceous hedges is needed.

389 Two main approaches can be used to find out relevant location of herbaceous hedges (Dosskey
390 *et al.*, 2011). The first approach assesses the capability of vegetated areas to reduce runoff and
391 sediment transport through infiltration and sediment retention processes. This means using soil
392 and slopes properties to determine the infiltration capacity of the vegetated area which allows
393 to calculate indexes such as the ‘Sediment Trapping Efficiency’ of the herbaceous hedge
394 (Dosskey *et al.*, 2011). The second approach performs terrain analysis through GIS use,
395 especially on elevation dataset (Digital Elevation Model), to predict the runoff spatial patterns.
396 The elevation dataset is processed to create the flow direction and the flow accumulation. The
397 resulting data enables to map the hydrological network used by the runoff and to delineate the
398 watersheds or specific catchment areas of previously selected places, such as field limits or
399 human infrastructures. Existing models focus on vegetative filter strips, based on their specific
400 design, to evaluate the vegetation efficiency towards sediment retention. These models can be
401 used by practitioners to evaluate the vegetation effect on soil erosion processes and runoff, at
402 the field or the catchment scale. They are based on hydraulic roughness coefficients, such as
403 the Manning’s number n or the Darcy-Weisbach's coefficient f , and some basic plant
404 characteristics (Govers *et al.*, 2007). They usually focus on a limited number of plant and
405 vegetation characteristics. The field scale-based models VFSMOD and TRAVA define the
406 effects of the vegetative filter strips using the vegetation height and density (Deletic, 2001;
407 Muñoz Carpena & Parsons, 2014); while WEPP uses plant growth (aboveground and roots),
408 height, the stem basal area and the leaf area index (Arnold *et al.*, 1995). The catchment scale
409 model SWAT focus on the plant height, spacing and coverage, the leaf area index and the root
410 depth (Arnold *et al.*, 2012). Others does not integrate any plant characteristics but the

411 Manning's hydraulic roughness coefficient (e.g. CREAMS), or the width of the vegetative filter
412 strip (e.g. LISEM) (de Roo *et al.*, 1998; Williams & Nicks, 1988). Results on the effects of
413 plant traits in herbaceous hedges on the hydraulic resistance and sediment retention have
414 emphasised the effects of numerous traits not used in models (e.g. stem density, stem diameter,
415 leaf area and leaf density). Implementing these traits recognised as efficient to increase the
416 hydraulic resistance and sediment retention into the models would improve the precision of the
417 model results and help better select the best implantation location. Perspective is to integrate
418 the effects of these traits into the models at both field and catchment scales, and to validate the
419 model predictions compared to the empirical approach.

420

421

422 **Conclusion**

423 This review on the effects of plant functional traits in herbaceous vegetation on the hydraulic
424 resistance and sediment transfer has allowed the improvement of the understanding of the
425 vegetation roles on runoff, sediment retention and erosion control, facilitating the design of
426 herbaceous hedges for these purposes. Leaf and stem traits (i.e. leaf area, leaf density, stem
427 diameter, stem projected area and stem density) directly increase the hydraulic resistance and
428 sediment retention in herbaceous vegetation, especially when they are density-weighted, in
429 temperate agricultural catchments. The knowledge of these highlighted traits to illustrate the
430 vegetation effects on the hydraulic resistance and sediment retention is transposable to different
431 pedoclimatic contexts, with the characterisation of the intensity of the concentrated runoff (e.g.
432 slope and soil texture). The challenge of designing vegetation structures for soil erosion and
433 runoff mitigation is to include the plant traits involved in the increase of the hydraulic resistance
434 and sediment retention into the modelling of the vegetation effects by using existing models
435 for soil erosion control. Herbaceous hedges showing dense perennial herbaceous vegetation on

436 a narrow strip constitute a major structure to reduce concentrated flows and soil erosion under
437 temperate climates in agricultural catchments. Their design should consider (1) the selection
438 method based on the functional types and traits of the indigenous species located in the
439 implantation area; (2) the number of species and their traits composing the hedge, as choosing
440 if the hedge should comprise several species with contrasting traits and (3) the positioning of
441 the hedges using multi-scale analysis and modelling. Perspective is to unravel the contrasting
442 effects of the functional diversity on runoff and sediment retention by studying a wide gradient
443 of functional diversity within plant communities on these ecosystem processes. Comparison of
444 the functional diversity effects among several processes and services should also be examined
445 to design multifunctional ecosystems and specifically manage major ecosystem services in
446 each phytogeographical territory.

447

448

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456 **Data Availability Statement**

457 Data sharing not applicable to this article as no datasets were generated or analysed during the
458 current study.

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781 **Table 1. The 76-candidate species list potentially able to mitigate soil erosion in the north-**
782 **west European loess belt.**

783 The minimum vegetative heights are represented under the median value (Quartile 1; Quartile
784 4) of the data obtained from Hegi (1906); Jauzein and Nawrot (2011); Lambinon et al. (2012);
785 Mansion et al. (1989); Rothmaler and Jäger (2009); Bugnon (1995) *In* Université de Bourgogne
786 (UFR Science de la vie) (2018)). Hem.: Hemicryptophyte; C. Hem.: Caespitose
787 hemicryptophyte; Ch.: Chamaephyte; R. Hem: Rosette hemicryptophyte.

Family	Species name	Life form	Minimum vegetative height (cm)
Adoxaceae	<i>Sambucus ebulus L.</i>	Hem.	55 (50; 80)
Apiaceae	<i>Anthriscus sylvestris (L.) Hoffmann</i>	Hem.	45 (40; 80)
	<i>Bupleurum falcatum L.</i>	Hem.	30 (20; 50)
	<i>Heracleum sphondylium L.</i>	Hem.	50 (30; 50)
Asteraceae	<i>Achillea ptarmica L.</i>	Hem.	20 (20; 30)
	<i>Artemisia verlotiorum</i>	Hem.	70 (67.5; 150)
	<i>Artemisia vulgaris L.</i>	Hem.	60 (52.5; 60)
	<i>Aster laevis L.</i>	Hem.	60 (60; 60)
	<i>Aster salignus Willd.</i>	Hem.	80 (72.5; 90)
	<i>Eupatorium cannabinum L.</i>	Hem.	55 (50; 80)
	<i>Hieracium piloselloides Vill.</i>	Hem.	20 (20; 20)
	<i>Senecio jacobaea L.</i>	Hem.	30 (30; 40)
	<i>Tanacetum corymbosum L.</i>	Hem.	30 (30; 50)
<i>Tanacetum parthenium L.</i>	Hem.	30 (30; 30)	
<i>Tanacetum vulgare L.</i>	Hem.	55 (42.5; 60)	
Caryophyllaceae	<i>Saponaria officinalis L.</i>	Hem.	30 (30; 30)
Clusiaceae	<i>Hypericum perforatum L.</i>	Hem.	27.5 (21.25; 30)
Cyperaceae	<i>Carex acutiformis Ehrh.</i>	Hem.	50 (35; 50)
	<i>Carex binervis Smith</i>	C. Hem.	30 (30; 30)
	<i>Carex brizoides L.</i>	Hem.	25 (25; 30)
	<i>Carex canescens L.</i>	Hem.	20 (20; 25)
	<i>Carex otrubae Podp.</i>	Hem.	30 (30; 30)
	<i>Carex diandra Schrank</i>	Hem.	20 (20; 30)
	<i>Carex distans L.</i>	Hem.	22.5 (20; 30)
	<i>Carex divulsa Stokes</i>	C. Hem.	20 (20; 30)
	<i>Carex elongata L.</i>	C. Hem.	30 (30; 30)
	<i>Carex flacca Schreb.</i>	Hem.	20 (10; 20)

	<i>Carex flava</i> L.	Hem.	20 (20; 30)
	<i>Carex paniculata</i> L.	C. Hem.	40 (40; 50)
	<i>Carex pendula</i> Huds.	C. Hem.	50 (50; 60)
	<i>Carex pilosa</i> Scop.	Hem.	20 (20; 30)
	<i>Carex pseudocyperus</i> L.	C. Hem.	40 (40; 50)
	<i>Carex remota</i> Jusl. ex L.	C. Hem.	30 (22.5; 30)
	<i>Carex spicata</i> Huds.	C. Hem.	20 (10; 30)
	<i>Carex strigosa</i> Huds.	C. Hem.	35 (22.5; 50)
	<i>Carex sylvatica</i> Huds.	C. Hem.	20 (12.5; 30)
	<i>Carex vulpina</i> L.	C. Hem.	30 (30; 40)
Lamiaceae	<i>Calamintha nepeta</i> (L.) Savi	Hem.	30 (27.5; 30)
	<i>Clinopodium vulgare</i> L.	Hem.	25 (20; 30)
	<i>Mentha longifolia</i> L.	Hem.	40 (30; 50)
	<i>Mentha spicata</i> L.	Hem.	35 (27.5; 50)
	<i>Mentha suaveolens</i> Ehrh.	Hem.	25 (16.25; 40)
	<i>Origanum vulgare</i> L.	Ch.; Hem.	25 (20; 40)
Linaceae	<i>Linum perenne</i> L.	Hem.	25 (22.5; 30)
Papaveraceae	<i>Meconopsis cambrica</i> (L.) Vig.	Hem.	30 (25; 40)
Poaceae	<i>Agrostis gigantea</i>	Hem.	30 (30; 40)
	<i>Arrhenatherum elatius</i> L.	Hem.	60 (50; 70)
	<i>Brachypodium pinnatum</i> (L.) Beauv.	Hem.	40 (32.5; 60)
	<i>Brachypodium sylvaticum</i> (Huds.) Beauv.	Hem.	50 (50; 60)
	<i>Bromus erectus</i> Huds.	Hem.	30 (30; 30)
	<i>Bromus inermis</i> Leyss.	Hem.	30 (30; 50)
	<i>Bromus ramosus</i> Huds.	Hem.	70 (45; 100)
	<i>Calamagrostis arundinacea</i> (L.) Roth	C. Hem.	60 (60; 60)
	<i>Calamagrostis epigejos</i> (L.) Roth	Hem.	60 (45; 60)
	<i>Calamagrostis varia</i> (Schrad.) Host	Hem.	40 (40; 50)
	<i>Calamagrostis villosa</i> (Chaix ex Vill.) J.F. Gmel.	Hem.	60 (45; 60)
	<i>Cynosurus cristatus</i> L.	Hem.	20 (20; 30)
	<i>Dactylis glomerata</i> L.	Hem.	20 (20; 50)
	<i>Deschampsia cespitosa</i> (L.) Beauv.	Hem.	30 (30; 50)
	<i>Deschampsia flexuosa</i> (L.) Trin.	C. Hem.	25 (20; 30)
	<i>Festuca arundinacea</i> Schreb.	Hem.	60 (40; 70)
	<i>Festuca gigantea</i> (L.) Vill.	Hem.	55 (50; 60)
	<i>Festuca heteropachys</i> (St-Yves) Patzke ex Auquier	C. Hem.	27.5 (23.75; 40)
	<i>Festuca heterophylla</i> Lam.	C. Hem.	40 (40; 60)
	<i>Festuca longifolia</i> Thuill.	C. Hem.	20 (20; 30)
<i>Festuca marginata</i> (Hack.) K. Richt.	C. Hem.	20 (18.75; 20)	
<i>Festuca polesica</i> Zapal.	C. Hem.	20 (20; 20)	
<i>Festuca pratensis</i> Huds.	Hem.	30 (30; 40)	
<i>Festuca rubra</i> L.	Hem.	30 (20; 40)	

	<i>Koeleria pyramidata (Lam.) Beauv.</i>	Hem.	20 (20; 45)
	<i>Melica ciliata L.</i>	Hem.	22.5 (20; 30)
	<i>Melica nutans L.</i>	Hem.	30 (22.5; 30)
	<i>Melica uniflora Retz.</i>	Hem.	25 (20; 30)
	<i>Milium effusum L.</i>	Hem.	55 (50; 80)
	<i>Phalaris arundinacea L.</i>	Hem.	50 (50; 80)
Rosaceae	<i>Filipendula ulmaria (L.) Maxim.</i>	R. Hem.	50 (50; 100)

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790 **Table 2. Minimal threshold values of the efficiency range of each trait and density-**
 791 **weighted trait on the hydraulic resistance and sediment retention.**

792 The threshold values were identified using the results from the generalised linear regression
 793 models in Kervroëdan et al. (2018). It represents the intersection between the USP critical value
 794 and the regression curve. As leaf area and density had different responses toward the hydraulic
 795 resistance depending on the discharge, the non-significant effects for the relevant discharges
 796 were darkened. The combination of both leaf area and leaf density was found to explain better
 797 the effects on the hydraulic resistance for all discharges rather than the traits taken separately.

	2 L.s ⁻¹ .m ⁻¹	4 L.s ⁻¹ .m ⁻¹	8 L.s ⁻¹ .m ⁻¹	11 L.s ⁻¹ .m ⁻¹
Leaf area (mm ²)	200	2200	6500	8200
Leaf density (m ⁻²)	0	7000	25000	31000
W. leaf area (mm ² .m ⁻²)	200000	22750000	82000000	100000000
W. projected stem area (mm ² .m ⁻²)	200000	840000	1875000	2350000
W. stem diameter (mm.m ⁻²)	2000	8000	19000	23000

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