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

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Abstract

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

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

Key-words

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

1. Introduction

Soil erosion by water is influenced by precipitation, soil texture and structure, slopes that can generate intense discharges, and plant and litter covers which vary according to cultural practices in cultivated areas. Intense runoff and soil erosion are frequently found in north-western European catchments where the sloping loamy soils are intensively tilled and cultivated with annual crops (Boardman and Poesen, 2006; Gobin et al., 2003). In the European loess belt, erosion can be mitigated by both (1) tillage reduction and the establishment of cover crops during sensitive seasons which increase the crop residue quantity on soil surface and thus, reduce the rill and inter-rill soil erosion (Knapen et al., 2007), and (2) establishment of vegetative barriers across the thalweg to mitigate rill and ephemeral gully erosion (Richet et al., 2017). Richet et al. (2017) demontrated the effects of fascines (i.e. vegetative barriers made of bundles of stems) on hydraulic roughness and soil erosion mitigation however, their short lifetime and high cost represent a main limitation. Herbaceous hedges, defined as narrow strips of dense and stiff perennial vegetation, constitute a major interest to develop vegetative barriers with a high efficiency on the reduction of soil erosion at lower cost against concentrated flows (Dabney et al., 1995; Yuan et al., 2009). Besides, herbaceous hedges composed of indigenous plant species could offer other ecosystem services than regulating services such as the provision of habitats and their ecological connectivity in these catchments (Ouin and Burel, 2002; Smith et al., 2008).

The effect of herbaceous vegetation on runoff and soil erosion, have been studied over the past decades (Haan et al., 1994; Lambrechts et al., 2014; Ludwig et al., 2005; Temple et al., 1987). Blanco-Canqui et al. (2006), Dosskey et al. (2010), Lambrechts et al. (2014), Le Bissonnais et al. (2005), Ruiz-Colmenero et al. (2013) and Stokes et al. (2014) noted the direct effects of vegetation cover on splash detachment and inter-rill erosion reduction. The impact of plant roots on infiltration capacity and resistance of soils to erosion by water has been well documented (Berendse et al., 2015; Dabney et al., 2009; De Baets et al., 2006; De Baets and Poesen, 2010; Gyssels et al., 2005; Isselin-Nondedeu and Bédécarrats, 2007; Lambrechts et al., 2014). The influence of vegetation on sediment retention was highlighted (Burylo et al., 2012; Dabney et al., 2009; Dillaha et al., 1989; Haan et al., 1994; Isselin-Nondedeu and Bédécarrats, 2007; Lowrance et al., 1995). The relationship between vegetation and sediment retention can be understood only if the vegetation effect on hydraulic roughness, which is the frictional resistance due to the contact of runoff with the vegetation, is characterised, as it is the main process with gravity furthering sediment retention. This effect has been previously investigated (Akram et al., 2014; Cantalice et al., 2015; Cao et al., 2015; Haan et al., 1994; Järvelä, 2002; Temple et al., 1987). The presence of herbaceous vegetation has positive impacts on hydraulic roughness, as it reduces flow velocity and increases backwater depth (Akram et al., 2014; Cantalice et al., 2015; Hussein et al., 2007), thereby increasing sediment retention due to its linear relationship with backwater depth (Dabney et al., 1995; Hussein et al., 2007; Meyer et al., 1995). Plant effects on hydraulic roughness are highly variable among species and are difficult to explain without characterisation of all aboveground morphological traits (Cantalice et al., 2015; Cao et al., 2015; Dabney et al., 1995). The relationship between aboveground plant morphology and hydraulic roughness should be specified to globally understand runoff and soil erosion processes.

One of the challenges to improving the understanding in plant and vegetation (e.g. herbaceous hedges) effects on hydraulic roughness and soil erosion is the development of a functional trait-based approach (Faucon et al., 2017). This approach, which allows for characterising trait effects on ecosystem processes and services (Lavorel and Garnier, 2002), has been developed with the establishment of the relationship between the soil detachment ratio and root length density for underground biomass (De Baets and Poesen, 2010; Mekonnen et al., 2016; Vannoppen et al., 2015). Concerning aboveground characteristics, trait-based approaches highlighted the relationships between stem density, diameter and stiffness, and between leaf area and density with sediment retention (Bochet et al., 2000; Burylo et al., 2012; Mekonnen et al., 2016; Zhu et al., 2015). Because the hydraulic roughness is one of the main process influencing sediment retention, plant functional traits known to influence sediment retention could influence the hydraulic roughness. Those traits, such as the stem and tiller density (Hayes et al., 1978; Isselin-Nondedeu and Bédécarrats, 2007; Morgan and Duzant, 2008; Temple, 1982), stem diameter (Bochet et al., 2000; Meyer et al., 1995; Morgan and Duzant, 2008), stem stiffness (Dabney et al., 2009; Meyer et al., 1995), specific leaf area (Graff et al., 2005), leaf area (Burylo et al., 2012) and leaf density (Lambrechts et al., 2014), should be considered to specifically characterise the effect of aboveground traits on hydraulic roughness. In addition to characterising vegetation effects on hydrological processes and, notably, hydraulic roughness, the weight of traits in the vegetation should be considered (Garnier and Navas, 2012) to improve the overall understanding of soil erosion.

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

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

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

2. Materials and methods

2.1. Plant materials

Fourteen plant species that display contrasting aboveground morphological traits were chosen from 76 candidate species, resulting in six filters of selected functional types involved in mitigation of soil erosion in north-west Europe applied to the 3,500 spermatophyte species from north-west Europe (Lambinon et al., 2012). These selective filters were as follows: (1) Raunkiaer's life-form categories of "herbaceous chamaephytes", "hemicryptophytes" and "geophytes", i.e., perennial herbaceous vegetation that provide an effective soil cover during all seasons; (2) the presence of fresh (i.e., herbaceous chamaephytes and caespitose hemicryptophytes) or dry (i.e., non-caespitose hemicryptophytes and geophytes) biomass in winter when soil erosion is observed in north-west Europe (Boardman and Poesen, 2006); (3) the presence of rhizomes or stolon to ensure lateral spreading capacity and burial tolerance due to sediment deposition; (4) vegetative height ≥ 20 cm, as it is the water maximal level in the catchment in north-west Europe; (5) a broad ecological niche to select species able to grow in several silty agricultural soils; and (6) non-weed species to prohibit their expansion in agricultural territories of north-west Europe.

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

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

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

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

2.2. Plant morphological trait measurements

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

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

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

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

2.3. Hydraulic measurements

We used the same runoff simulator as Richet et al. (2017) to quantify the effect of plant morphological traits on hydraulic roughness (Fig. 1). The simulator allowed the recreation of a flow at chosen discharges and the measurement of hydrological parameters resulting from the presence of plants. The upper and lower parts of the simulator are equipped with flowmeters made of Venturi channels with a flow range of 0.06 $L.s^{-1}$ to 6 $L.s^{-1}$, comprising ultrasound probes that measure the water level in the channel at ± 1.26 mm. This system was manufactured by ISMA, France (Richet et al., 2017). The water was circulating within the system, with the aid of two pumps and a reservoir, in a closed circuit. The central part of the simulator is a channel setup with two galvanised iron sheets. The channel was 60 cm wide and 5.40 m long along a 5% slope. The entire channel was waterproofed using a plastic tarpaulin to avoid any water loss during the experiments. The tarpaulin was placed in order to obtain a smooth channel bottom and limit bottom roughness as much as possible. The roughness of the tarpaulin was determined by experiment using a control plot without any plants and represented a small percentage of the roughness created by the plants (Appendix B). The vegetation was placed 4 m away from the head of the channel, in a 17 cm deep rectangular hole to level the ground with the flow and the slope. The tarpaulin used in the upper part of the channel was placed continually underneath the plot and through the lower part of the channel to avoid water loss by infiltration. The boundary effects were minimal as the plants were left in the wooden frame where they grew, and a wooden plank was placed along each side the entire channel. The small gap areas along the base of the planks and the bottom of the channel were sealed using clay. Along the channel, 7 spacers were set up to measure the topography of the channel bed and the water heights in the backwater and downstream of the plot. Five were located upstream of the plants and two were located downstream. Approximately 1.46 m from the channel head, the spacers were spaced at 0.75 m.

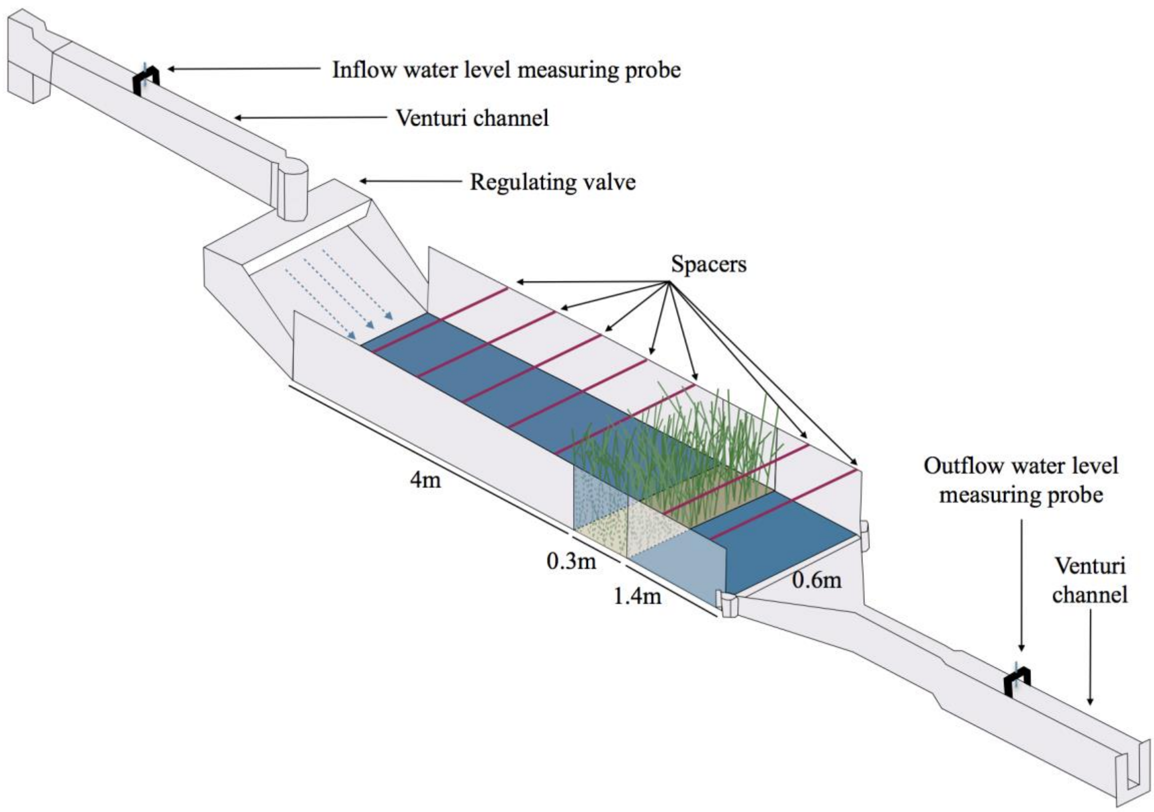

Figure 1. Runoff simulator used during the study.

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

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

$$USP = V\,S \qquad (1)$$

where *USP* is expressed in $m.s^{-1}$, V is the mean velocity ($m.s^{-1}$), and S is the channel slope ($m.m^{-1}$) (Cao et al., 2015; Hessel et al., 2016; Morgan et al., 1998). The lower the *USP* is, the greater the hydraulic roughness will be. The mean velocity was calculated using the water levels measured at the closest spacer upstream of the plot. Govers (1990) determined a *USP* critical value of 0.004 $m.s^{-1}$ that indicates that the threshold from which soil is most likely to erode in the loamy soils found in the European loess belt. Govers (1990) established this critical value for bare loess soils with a D_{50} from 58 µm to 218 µm, at slopes ranging from 1° to 8° and for discharges varying from 0.2 to 10 $L.s^{-1}.m^{-1}$. The *USP*, Manning coefficients and backwater depths are presented in Appendix B.

2.4. Data analysis

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

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

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

3. Results

3.1. Variations of plant morphological traits

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

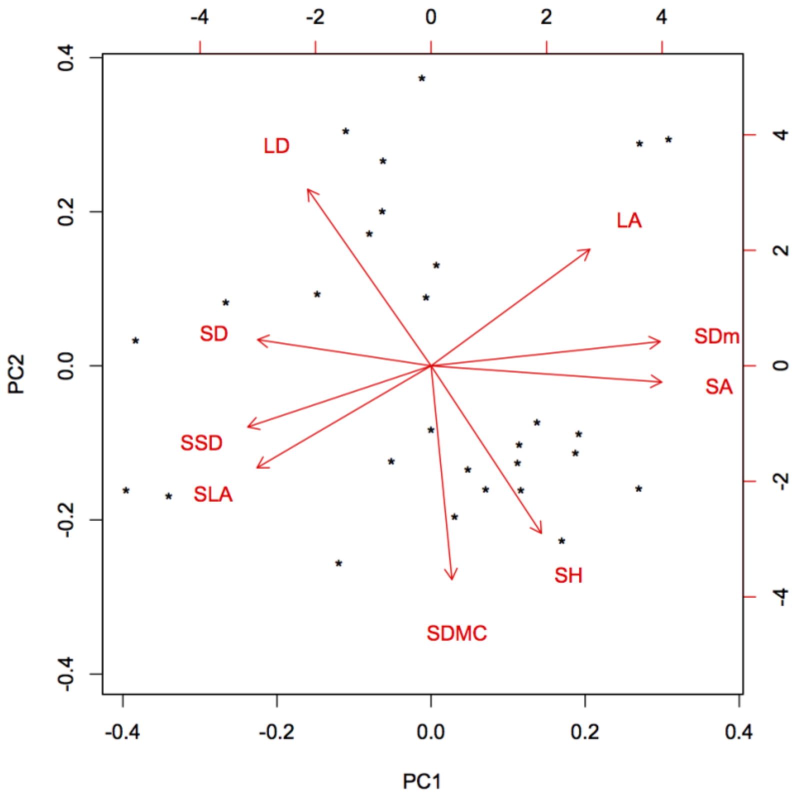

Figure 2. Principal component analysis of nine morphological traits measured on 14 plant species. PC1 explained 47% of the variance and PC2 explained 24.9%. LA = leaf area, LD = leaf density, SA = projected stem area, SD = stem density, SDm = stem diameter, SDMC = stem dry matter content, SLA = specific leaf area, SSD = stem specific density. The vegetative stem height (SH) was added to the other traits for this analysis.

3.2. Effect of morphological traits on the Unit Stream Power

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

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

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	ß	AIC	ß	AIC	ß	AIC	ß
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; ß = regression coefficient; *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; ns = not significant. The significant correlations are indicated in bold.

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

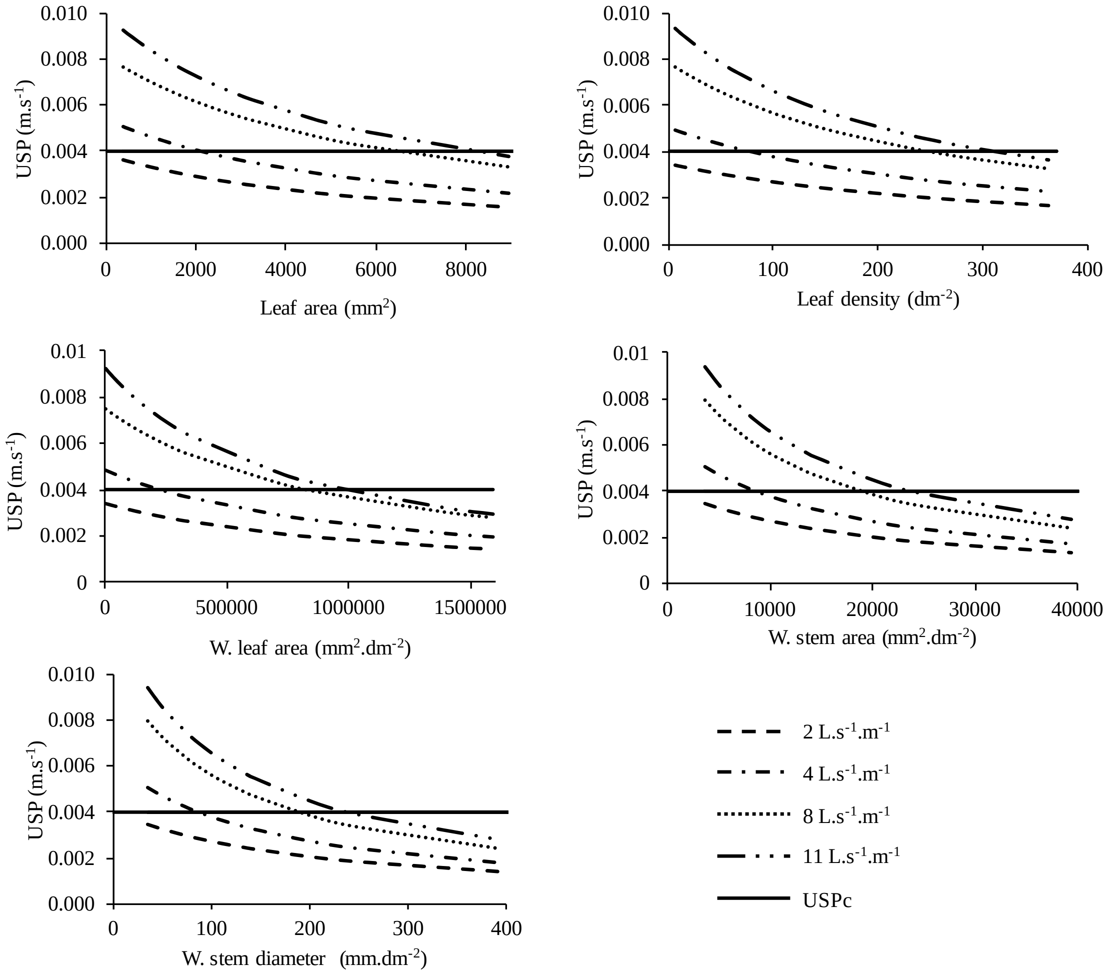

Figure 3. Relationship between *USP* and traits and density-weighted traits identified as the best fit to hydraulic roughness at 0 – 10 cm. USPc represents the threshold of 0.004 m.s^{-1} from which soil is likely to erode in loamy soils found in the European loess belt (Govers, 1990).

Table 4. Selected GLMs fitted to *USP* and two traits as estimation variables for each discharge used. The models are sorted from the smallest ΔAICc to the highest ΔAICc at each discharge used.

Discharge	Models	AICc	ΔAICc	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 ΔAICc and wAICc. LA = leaf area and LD = leaf density

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

4. Discussion

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

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

Stem and leaf traits influenced hydraulic roughness, given that they constitute a hydraulic brake on water flows. However, some stem and leaf traits may have a greater effect on hydraulic roughness. This study has highlighted that, among the considered aboveground traits involved in soil erosion (i.e., leaf area, SLA, leaf density, stem density, stem diameter, stem specific density, projected stem area and stem dry matter content), only the leaf area and the leaf density presented a significant effect on hydraulic roughness. The leaf traits have a better impact on hydraulic roughness than stem traits, regarding non-weighted traits. The GLMs showed that the combination of leaf density and leaf area better explained the effect on hydraulic roughness than these traits alone for any discharge used. Plant individuals with better trade-off between leaf density and leaf area, meaning high leaf density and long leaves, such as some graminoid species, would have a great impact on mitigating the unit stream power and thus increase hydraulic roughness. These results are in agreement with other studies highlighting the efficiency of several graminoid species in soil erosion mitigation (Isselin-Nondedeu and Bédécarrats, 2007; Morgan, 2004). The absence of the stem density effect on hydraulic roughness is not in agreement with the literature where the stem density is considered a main trait impacting flow velocity and soil erosion (Isselin-Nondedeu and Bédécarrats, 2007; Mekonnen et al., 2016; Meyer et al., 1995; Morgan and Duzant, 2008; Temple et al., 1987). This contradiction could be explained by the lack of a standard characterisation of all stem and leaf traits involved in hydraulic roughness and soil erosion (e.g. defining the tillers and pseudoculms as stems when characterising the stem density). The stem density is one of the main traits included in hydraulic and soil erosion models such as VFSMOD (Muñoz Carpena and Parsons, 2014) and in studies focusing on the relationship between vegetation and hydraulic roughness or sediment retention (Morgan, 2004; Temple, 1982; Van Dijk et al., 1996; Xiao et al., 2011), which could be improved by considering the effect of other stem traits (e.g., stem diameter). In the trait-based approach, the importance of stem density in the plant-hydraulic roughness relationship lays in its use in the calculation of weighted stem trait values in the vegetation. Indeed, this approach highlighted that mainly density-weighted traits influenced hydraulic roughness. Specifically, all the GLMs included weighted leaf area, indicating its great importance in the increase of hydraulic roughness. Projected stem area or stem diameter showed no significance on the hydraulic roughness at the trait level but, by considering weighted stem traits, weighted projected stem area and weighted stem diameter showed highly significant effects on the unit stream power. The GLMs showed that the best fit model was WSA + WLA (weighted projected stem area + weighted leaf area) as these traits represent the interception area of the leaves and stems with the water flow in the vegetation, i.e., a hydraulic brake. As the stem diameter, projected stem area and leaf area were negatively associated with the stem density, trade-offs among these stem and leaf traits can be considered to improve herbaceous hedge effects on hydraulic roughness. The effect of weighted SLA, when associated with weighted leaf area and weighted stem diameter or weighted leaf area and weighted projected stem area, was also observed ($3 < \Delta \mathrm{AICc} < 5$). Overall, vegetation presenting the best trade-off between stem density and weighted stem diameter, as well as between leaf density and leaf area, will have a greater efficiency to increase hydraulic roughness. Herbaceous hedges that present these weighted leaf and stem traits would be partly composed of graminoid species, given that these present large leaf density, leaf area, stem diameter and a greater hydraulic roughness than non-graminoid species (Isselin-Nondedeu and Bédécarrats, 2007). Stem and leaf densities should be considered to calculate weighted-traits in herbaceous hedges and quantify the effect on soil erosion. Characterisation of trait weights in herbaceous hedges vegetation allowed to highlight the main morphological aboveground traits and their combinations involved in hydraulic roughness, as well as the importance of stem density as a plant marker to examine the effect of vegetation on runoff. As a result, this trait-based approach can be effectively applied at the vegetation level to understand and model runoff and soil erosion.

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

Flow rate variations can trigger different soil-plant-water processes (Dabney et al., 2004; Temple et al., 1987; Vieira and Dabney, 2012). The results here are consistent with the hypothesis that the influence of aboveground traits on hydraulic roughness can change with the discharge. The effect of leaf density (0-20 cm) and leaf area on hydraulic roughness varied with the discharge. The results showed the importance of leaf density in increasing hydraulic roughness at higher discharges ($\Delta \mathrm{AIC} < 2$). However, for lower discharges, a combination of leaf area and leaf density should be considered rather than the traits alone. The results for the leaf area are in accordance with the one found by Temple et al. (1987) showing a decreasing impact of the leaf structure with an increasing discharge. At a small discharge (2 $L.s^{-1}.m^{-1}$), weighted SLA (0-10 cm) did not present an effect on the hydraulic roughness, but a positive influence was observed at 4 $L.s^{-1}.m^{-1}$. Differences in the influence of leaf density and weighted SLA among the discharges may be interpreted as the water depth being too low to enter into contact with all the leaves between 0 and 20 cm of each individual and with large SLA until 5 cm of the vegetation at small discharges. Herbaceous hedges, playing a key role in hydraulic roughness, presents the best trade-off between stem density and diameter, as well as leaf density and area at low discharges, and with increasing water discharge, larger basal leaf density and basal SLA. This study indicates that some trait and density-weighted trait effects on hydraulic roughness are linked to the flow water level. The characterisation of these effects according to flow depth constitutes an advance to model water flows and soil erosion in ecosystems and landscapes.

4.3. Consequences on sediment retention

As hydraulic roughness is linked to sediment retention and transport capacities (Dabney et al., 2009; Isselin-Nondedeu and Bédécarrats, 2007; Lambrechts et al., 2014; Munoz-Carpena et al., 1999), plant morphological traits, which have positive effects on hydraulic roughness, can be discussed with studies highlighting plant trait effects on sediment retention. Indeed, results showed the positive effect of the leaf area on hydraulic roughness, whereas there was no effect of stem specific density at small discharges, such as 2 $L.s^{-1}.m^{-1}$, which is consistent with Burylo et al. (2012) on the sediment retention capacity for more intense erosion processes. Results display the greater impact of density-weighted traits, which were previously not considered in studies on plant trait effects on sediment retention. The density-weighted trait approach is therefore important in understanding the plant-soil interaction involved in soil erosion.

Application of this trait-based approach in ecohydrology involves using the results to manage the reduction of soil erosion. Use of the unit stream power allows to characterise the plant efficiency with regard to sediment retention, with a critical *USP* (USPc) value of 0.004 $m.s^{-1}$ determined by (Govers, 1990), which indicates the threshold from which soil is most likely to erode in loamy soils found in the European loess belt. From identified traits and density-weighted traits presenting an effect on hydraulic roughness and their values (USP < 0.004 $m.s^{-1}$) plant species selection could be performed to create new herbaceous ecosystems that will be efficient to reduce runoff and further sediment retention on degraded areas (e.g., bare soils in degraded agroecosystems, urban and mining habitats) (Fig. 3).

5. Conclusions

This trait-based ecohydrology study allows the identification of important plant traits that influence the hydraulic roughness. The results indicate the stronger effect of density-weighted traits, showing that communities with the best trade-offs between stem density, diameter and leaf area are the key to mitigate soil erosion. This new knowledge in the relationship between plant functional traits with hydraulic roughness and soil erosion constitutes a new advancement for modelling vegetation effects on soil erosion and creating new herbaceous ecosystems in degraded areas (e.g. bare soils of agroecosystems, mining and urban habitats). These newly reconstructed herbaceous ecosystems will play an important role in soil erosion mitigation. Future work should (1) include these relationships between aboveground traits and hydraulic roughness in existing models to estimate the transport and sediment retention capacities of flows and design herbaceous hedges to mitigate soil erosion and (2) examine the effect of functional diversity on runoff and soil erosion, as it could influence hydraulic roughness by ecologically complementing aboveground biomass and, more precisely, by limiting vegetation lodging.

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