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

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Key-words

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

Abstract

Aims

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

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

Methods

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

Results

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

Conclusion

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

Introduction

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

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

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

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

Materials and methods

Plant material

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

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

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

Experimental site design

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

In October 2016, one year *prior* experiments, the plants were planted in 1m² plots with a density of 53 young plants.m⁻² (Fig. 1). The multi-specific plots were planted with the same proportion of each species and the young plants were placed so young plants of the same species would not be next to each other. A control condition, with no vegetation, was also tested with three replicates to compare the effects of the traits between each species. Each of the 15 plots was

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

Hydraulic measurements

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

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

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

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

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

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

Sediment retention

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

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

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

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

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

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

Leaf and stem trait measurements

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

analyses methods were conducted following the standardised guidelines from (Pérez-Harguindeguy et al. 2013). The leaves were collected in sealed bags with moist tissue until measurements were performed and then, dried at 70°C for 72h. The traits were all measured within one quadrat (10 by 10 cm) per monospecific community plot and one quadrat per species within the multi-specific community plots, due to the homogeneous plant cover within the plots. The leaf density (leaves.m⁻²) was measured for each level along the stems by counting fresh and dry leaves. The leaf area (mm²) and specific area (mm².mg⁻¹) were determined using six representative leaves, scanned at 600dpi resolution, and the images were analysed using Gimp 2.8. Pseudoculms for sedges species (Cyperaceae) and tillers for grass species were counted with the stems to measure the stem density (stems.m⁻²). The stem diameter (mm) was measured for each level on three representative stems and was used to calculate the projected stem area (mm²), using the rectangle area formula. The aboveground biomass (g) was estimated by collecting a 50 x 50 cm quadrat in each plot and dried during 72h at 70°C. The species biomass in the multi-specific plots were separated in order to determine the biomass productivity of each species.

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

Characterisation of the trait diversity effects on the hydraulic roughness and sediment retention

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

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

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

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

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

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

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

Data analyses

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

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

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

Results

The traits in the monospecific conditions and their effects on the unit stream power and sediment retention

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

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

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

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

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

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

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

Discussion

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

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

Syversen and Borch 2005). This was especially observed for *T. vulgare* (for particles $<2\ \mu\text{m}$) which presented significantly lower density-weighted leaf areas and thus, a lower hydraulic roughness.

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

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

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

Conclusions

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

Authors' Contributions

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

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

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

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

Fig. 3 Runoff simulator used for the experiments.

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

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