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

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**Abstract**

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

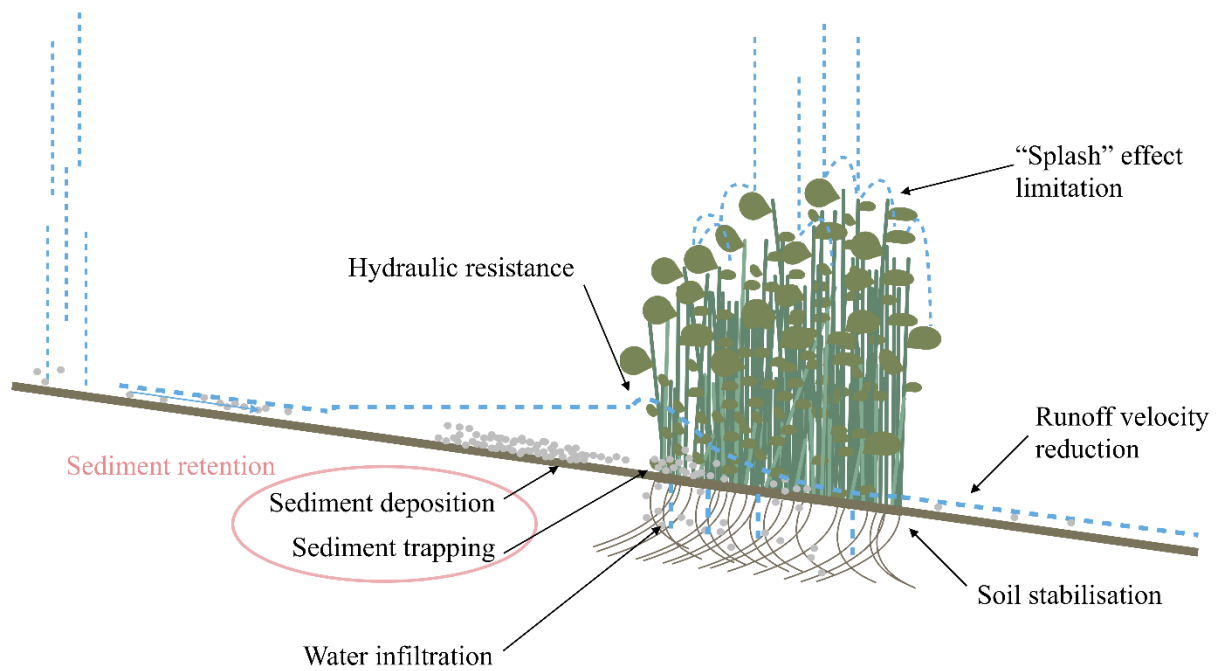
hydraulic resistance and sediment retention, within agricultural catchments. Using this knowledge, we propose applications of the trait-based approach to design and manage herbaceous hedges for sediment retention and soil erosion control. This review synthesises recent advances regarding the effects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

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

## 1. Introduction

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

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



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

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

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

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

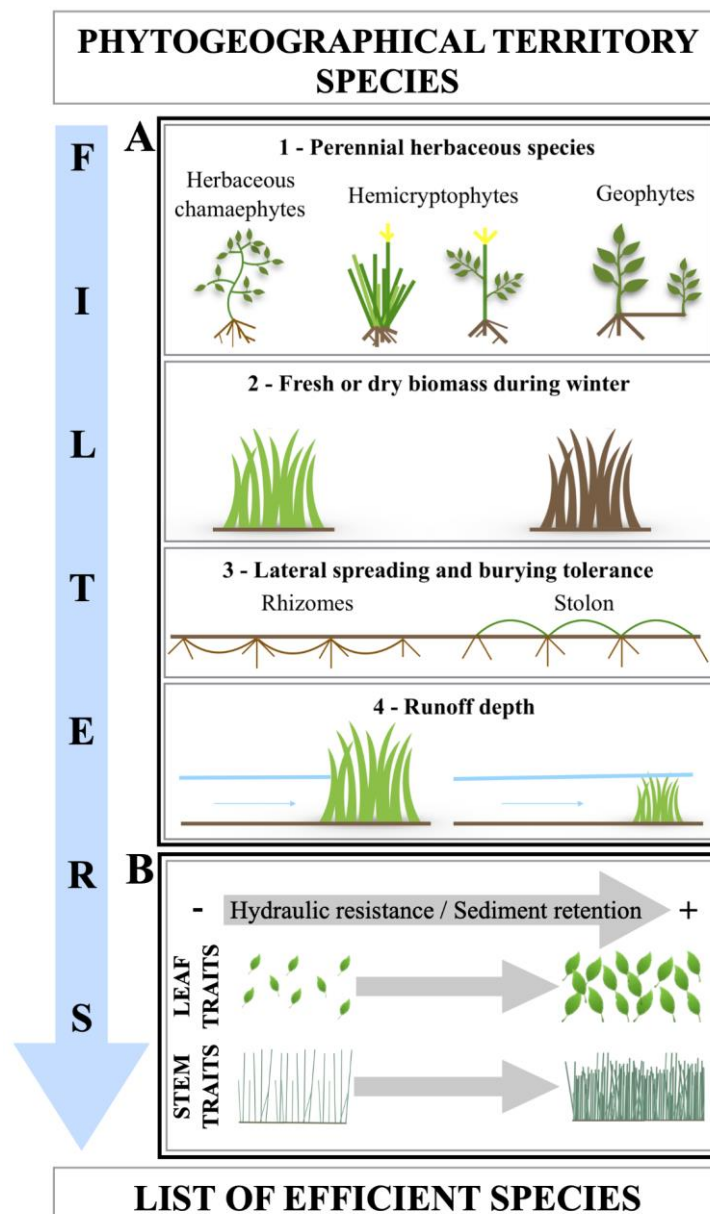
(1) the influence of plant aboveground functional types and traits on the hydraulic resistance and sediment retention; (2) the contentious effects of the functional diversity on the hydraulic resistance and sediment retention and (3) the applications of the trait-based approach for the design and the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

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

### **2.1. Effects of the plant functional types**

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

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



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



## 2.2. Effects of leaf and stem functional traits

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

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

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

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

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

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

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

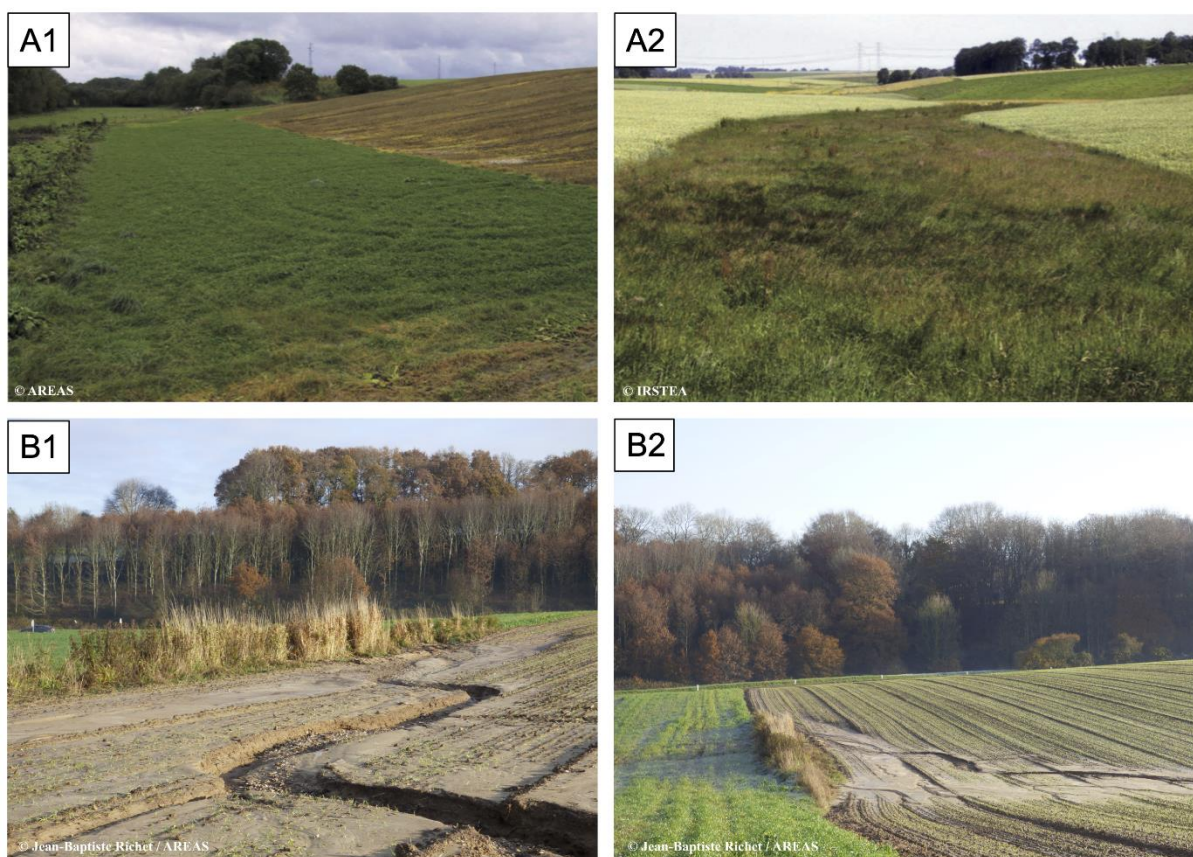
– was highlighted to be a better predictor to characterise the effects of plant diversity on ecosystem processes (Cadotte *et al.*, 2011), such as runoff and soil erosion.

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

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

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

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



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

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

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

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

### 3.2. Monospecific or multi-specific herbaceous hedges?

Biodiversity usually corresponds to a more ecologically stable system, as a stable and healthy system would be less vulnerable to abiotic and biotic stress (Tilman, 1999). Therefore, practitioners may ask if it is better to use only one or a few species that can efficiently increase sediment retention and mitigate runoff and soil erosion, or if a diverse range of species, sometimes less efficient, should be used. Most of the studied herbaceous hedges through the literature were monospecific hedges (Cao et al., 2015; Cullum et al., 2007; Dabney et al., 2004; Huang et al., 2010; Hussein et al., 2007; Lin et al., 2009; Liu et al., 2018; Mekonnen et al., 2016; Meyer et al., 1995). However, the use of multi-specific vegetation to control runoff and soil erosion has been studied (Bautista *et al.*, 2007; Berendse *et al.*, 2015; Erktan *et al.*, 2013; Hou *et al.*, 2016; Kervroëdan *et al.*, 2019; Martin *et al.*, 2010; Pohl *et al.*, 2009; Turnbull *et al.*, 2008; Zhang *et al.*, 2015; Zhu *et al.*, 2015), but some of the studies focussed on the diversity of different functional types or within vegetation patches. A positive effect of plant diversity was also found on the soil erosion resistance (Berendse *et al.*, 2015). Trait divergence showed positive effects on sediment retention and the hydraulic resistance in herbaceous vegetation in loamy agricultural catchments, although the efficiency of the multi-specific vegetation could be lowered by the presence of species with large stem (Kervroëdan *et al.*, 2019). Taking into account these contentious results and that species diversity within herbaceous hedges did not show negative interactions with the efficiency of the multi-specific hedges, it can be suggested using only few species with the best traits involved in decreasing runoff, increasing sediment retention and mitigating soil erosion in a same herbaceous hedge (Rey & Labonne, 2015). However, species diversity should be favoured as much as possible to: (1) enable reducing the risks of failure of vegetation systems in the case of the loss of a species on a site due to abiotic/biotic factors ((Berendse *et al.*, 2015; Doak *et al.*, 1998), and (2) provide other ecosystem services (e.g. habitat creation, ecological connectivity enhancement, 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.

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

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

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

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

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

## **Conclusion**

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

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

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## **Data Availability Statement**

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

## References

- Akram S, Yu B, Ghadiri H, Rose C, Hussein J. 2014. The links between water profile, net deposition and erosion in the design and performance of stiff grass hedges. *Journal of Hydrology* **510**: 472–479. DOI: 10.1016/j.jhydrol.2014.01.001
- Arnold JG, Kiniry JR, Williams JR, Haney EB, Neitsch SL. 2012. *Soil and water assessment tool*. Texas Water Resources Institute, 650
- Arnold JG, Weltz MA, Alberts EE, Flanagan DC. 1995. Chapter 8. Plant growth component. *USDA-Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation*. NSERL
- Balvanera P, Pfisterer AB, Buchmann N, He J-S, Nakashizuka T, Raffaelli D, Schmid B. 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services: Biodiversity and ecosystem functioning/services. *Ecology Letters* **9**: 1146–1156. DOI: 10.1111/j.1461-0248.2006.00963.x
- Bautista S, Mayor ÁG, Bourakhouadar J, Bellot J. 2007. Plant Spatial Pattern Predicts Hillslope Runoff and Erosion in a Semiarid Mediterranean Landscape. *Ecosystems* **10**: 987–998. DOI: 10.1007/s10021-007-9074-3
- Berendse F, van Ruijven J, Jongejans E, Keesstra S. 2015. Loss of plant species diversity reduces soil erosion resistance. *Ecosystems*. **18**: 881–888. DOI: 10.1007/s10021-015-9869-6
- Boardman J, Poesen J (eds). 2006. *Soil Erosion in Europe*. John Wiley & Sons, Ltd
- Bochet E, Poesen J, Rubio JL. 2000. Mound development as an interaction of individual plants with soil, water erosion and sedimentation processes on slopes. *Earth Surface Processes and Landforms* **25**: 847–867
- Bugnon F. 1995. *Nouvelle flore de Bourgogne, tome II : clés de détermination*. Bulletin scientifique de Bourgogne: Dijon, France
- Burylo M, Rey F, Bochet E, Dutoit T. 2012. Plant functional traits and species ability for sediment retention during concentrated flow erosion. *Plant and Soil*. **353**: 135–144. DOI: 10.1007/s11104-011-1017-2
- Cadotte MW. 2017. Functional traits explain ecosystem function through opposing mechanisms. *Ecology Letters* **20**: 989–996. DOI: 10.1111/ele.12796
- Cadotte MW, Carscadden K, Mirotchnick N. 2011. Beyond species: functional diversity and the maintenance of ecological processes and services. *Journal of Applied Ecology* **48**: 1079–1087. DOI: 10.1111/j.1365-2664.2011.02048.x
- Cantalice JRB, Melo RO, Silva YJAB, Cunha Filho M, Araújo AM, Vieira LP, Bezerra SA, Barros G, Singh VP. 2015. Hydraulic roughness due to submerged, emergent and flexible natural vegetation in a semiarid alluvial channel. *Journal of Arid Environments* **114**: 1–7. DOI: 10.1016/j.jaridenv.2014.10.012

498 Cao L, Zhang Y, Lu H, Yuan J, Zhu Y, Liang Y. 2015. Grass hedge effects on controlling  
 499 soil loss from concentrated flow: A case study in the red soil region of China. *Soil and*  
 500 *Tillage Research* **148**: 97–105. DOI: 10.1016/j.still.2014.12.009

501 Cao S. 2011. Impact of China's Large-Scale Ecological Restoration Program on the  
 502 Environment and Society in Arid and Semiarid Areas of China: Achievements,  
 503 Problems, Synthesis, and Applications. *Critical Reviews in Environmental Science*  
 504 *and Technology* **41**: 317–335. DOI: 10.1080/10643380902800034

505 Cao S, Chen L, Yu X. 2009. Impact of China's Grain for Green Project on the landscape of  
 506 vulnerable arid and semi-arid agricultural regions: a case study in northern Shaanxi  
 507 Province. *Journal of Applied Ecology* **46**: 536–543. DOI: 10.1111/j.1365-  
 508 2664.2008.01605.x

509 Carluer N, Lauvernet C, Noll D, Munoz-Carpena R. 2017. Defining context-specific  
 510 scenarios to design vegetated buffer zones that limit pesticide transfer via surface  
 511 runoff. *Science of the Total Environment* **575**: 701–712. DOI:  
 512 10.1016/j.scitotenv.2016.09.105

513 Cullum RF, Wilson GV, McGregor KC, Johnson JR. 2007. Runoff and soil loss from ultra-  
 514 narrow row cotton plots with and without stiff-grass hedges. *Soil and Tillage*  
 515 *Research* **93**: 56–63

516 Dabney SM, Meyer LD, Harmon WC, Alonso CV, Foster GR. 1995. Depositional patterns of  
 517 sediment trapped by grass hedges. *Transactions of the ASAE*. **38**: 1719–1729

518 Dabney SM, Shields Jr FD, Temple DM, Langendoen EJ. 2004. Erosion processes in gullies  
 519 modified by establishing grass hedges. *Transactions of the ASAE* **47**: 1561

520 De Baets S, Poesen J, Gyssels G, Knapen A. 2006. Effects of grass roots on the erodibility of  
 521 topsoils during concentrated flow. *Geomorphology*. **76**: 54–67. DOI:  
 522 10.1016/j.geomorph.2005.10.002

523 De Baets S, Poesen J, Reubens B, Muys B, De Baerdemaeker J, Meersmans J. 2009.  
 524 Methodological framework to select plant species for controlling rill and gully  
 525 erosion: application to a Mediterranean ecosystem. *Earth Surface Processes and*  
 526 *Landforms* **34**: 1374–1392. DOI: 10.1002/esp.1826

527 de Roo A, Jetten V, Wesseling C, Ritsema C. 1998. LISEM: A Physically-Based Hydrologic  
 528 and Soil Erosion Catchment Model. In: Boardman J and Favis-Mortlock D (eds)  
 529 *Modelling Soil Erosion by Water*. Springer: Berlin, Heidelberg, 429–440. DOI:  
 530 10.1007/978-3-642-58913-3\_32

531 Deletic A. 2001. Modelling of water and sediment transport over grassed areas. *Journal of*  
 532 *Hydrology* **248**: 168–182. DOI: 10.1016/S0022-1694(01)00403-6

533 Díaz S, Lavorel S, Chapin FS, Tecco PA, Gurvich DE, Grigulis K. 2007a. Functional  
 534 Diversity — at the Crossroads between Ecosystem Functioning and Environmental  
 535 Filters. In: Canadell JG, Pataki DE and Pitelka LF (eds) *Terrestrial Ecosystems in a*  
 536 *Changing World*. Springer Berlin Heidelberg: Berlin, Heidelberg, 81–91. DOI:  
 537 10.1007/978-3-540-32730-1\_7

- 538 Díaz S, Lavorel S, de Bello F, Quetier F, Grigulis K, Robson TM. 2007b. Incorporating plant  
539 functional diversity effects in ecosystem service assessments. *Proceedings of the*  
540 *National Academy of Sciences* **104**: 20684–20689. DOI: 10.1073/pnas.0704716104
- 541 Dillaha TA, Reneau RB, Mostaghimi S, Lee D. 1989. Vegetative filter strips for agricultural  
542 nonpoint source pollution control. *Transactions of the ASAE* **32**: 513–519
- 543 Doak DF, Bigger D, Harding EK, Marvier MA, O'Malley RE, Thomson D. 1998. The  
544 Statistical Inevitability of Stability-Diversity Relationships in Community Ecology.  
545 *The American Naturalist* **151**: 264–276. DOI: 10.1086/286117
- 546 Dosskey MG, Neelakantan S, Mueller TG, Kellerman T, Helmers MJ, Rienzi E. 2015.  
547 AgBufferBuilder: A geographic information system (GIS) tool for precision design  
548 and performance assessment of filter strips. *Journal of Soil and Water Conservation*  
549 **70**: 209–217. DOI: 10.2489/jswc.70.4.209
- 550 Dosskey MG, Qiu Z, Helmers MJ, Eisenhauer DE. 2011. Improved indexes for targeting  
551 placement of buffers of Hortonian runoff. *Journal of Soil and Water Conservation* **66**:  
552 362–372. DOI: 10.2489/jswc.66.6.362
- 553 Dosskey MG, Vidon P, Gurwick NP, Allan CJ, Duval TP, Lowrance R. 2010. The role of  
554 riparian vegetation in protecting and improving chemical water quality in streams.  
555 *Journal of the American water resources association* 1–18. DOI: 10.1111/j.1752-  
556 1688.2010.00419.x
- 557 Durán Zuazo VH, Rodríguez Pleguezuelo CR. 2008. Soil-erosion and runoff prevention by  
558 plant covers. A review. *Agronomy for Sustainable Development* **28**: 65–86. DOI:  
559 10.1051/agro:2007062
- 560 Erktan A, Cécillon L, Roose E, Frascaria-Lacoste N, Rey F. 2013. Morphological diversity of  
561 plant barriers does not increase sediment retention in eroded marly gullies under  
562 ecological restoration. *Plant and Soil* **370**: 653–669. DOI: 10.1007/s11104-013-1738-  
563 5
- 564 Faucon M-P, Houben D, Lambers H. 2017. Plant functional traits: soil and ecosystem  
565 services. *Trends in Plant Science* **22**: 385–394. DOI: 10.1016/j.tplants.2017.01.005
- 566 Flanagan DC, Ascough JC, Nearing MA, Laflen JM. 2001. The Water Erosion Prediction  
567 Project (WEPP) Model. In: Harmon RS and Doe WW (eds) *Landscape Erosion and*  
568 *Evolution Modeling*. Springer US: Boston, MA, 145–199. DOI: 10.1007/978-1-4615-  
569 0575-4\_7
- 570 Fullen MA. 1998. Effects of grass ley set-aside on runoff, erosion and organic matter levels  
571 in sandy soils in east Shropshire, UK. *Soil & Tillage Research* **46**: 41–49
- 572 Garnier E, Cortez J, Billès G, Navas M-L, Roumet C, Debussche M, Laurent G, Blanchard A,  
573 Aubry D, Bellmann A, Neill C, Toussaint J-P. 2004. Plant functional markers capture  
574 ecosystem properties during secondary succession. *Ecology* **85**: 2630–2637. DOI:  
575 10.1890/03-0799



- 576 Garnier E, Navas M-L. 2012. A trait-based approach to comparative functional plant ecology:  
577 concepts, methods and applications for agroecology. A review. *Agronomy for*  
578 *Sustainable Development* **32**: 365–399
- 579 Garnier E, Navas M-L, Grigulis K. 2016. *Plant Functional Diversity: Organism Traits,*  
580 *Community Structure, and Ecosystem Properties*. Oxford University Press
- 581 Gilley JE, Eghball B, Kramer LA, Moorman TB. 2000. Narrow grass hedge effects on runoff  
582 and soil loss. *Journal of Soil and Water Conservation* **55**: 190–196
- 583 Gilley JE, Kottwitz ER. 1995. Darcy-Weisbach roughness coefficients for surfaces with  
584 residue and gravel cover. *Transactions of the ASAE* **38**: 539–544
- 585 Gobin A, Govers G, Jones R, Kirkby M, Kosmas C, Gentile AR. 2003. *Assessment and*  
586 *reporting on soil erosion: Background and workshop report*. Technical. European  
587 Environment Agency: Copenhagen
- 588 Govers G. 1990. Empirical relationships for the transport capacity of overland flow.  
589 *International Association of Hydrological Sciences* **189**: 45–63
- 590 Govers G, Giménez R, Van Oost K. 2007. Rill erosion: Exploring the relationship between  
591 experiments, modelling and field observations. *Earth-Science Reviews* **84**: 87–102.  
592 DOI: 10.1016/j.earscirev.2007.06.001
- 593 Graff CD, Sadeghi AM, Lowrance RR, Williams RG. 2005. Quantifying the sensitivity of the  
594 riparian ecosystem management model (REMM) to changes in climate and buffer  
595 characteristics common to conservation practices. *Transactions of the ASAE* **48**:  
596 1377–1387
- 597 Grime JP. 1998. Benefits of plant diversity to ecosystems: immediate, filter and founder  
598 effects. *Journal of ecology* **86**: 902–910. DOI: 10.1046/j.1365-2745.1998.00306.x
- 599 Gumiere SJ, Bissonnais YL, Raclot D, Cheviron B. 2011. Vegetated filter effects on  
600 sedimentological connectivity of agricultural catchments in erosion modelling: a  
601 review. *Earth Surface Processes and Landforms* **36**: 3–19. DOI: 10.1002/esp.2042
- 602 Gyssels G, Poesen J, Bochet E, Li Y. 2005. Impact of plant roots on the resistance of soils to  
603 erosion by water: A review. *Progress in Physical Geography* **29**: 189–217. DOI:  
604 10.1191/0309133305pp443ra
- 605 Haan CT, Barfield BJ, Hayes JC. 1994. *Design Hydrology and Sedimentology for Small*  
606 *Catchments*. Academic Press
- 607 Hayes JC, Barfield BJ, Barnhisel RI. 1984. Performance of grass filters under laboratory and  
608 field conditions. *Transactions of the ASAE* **27**: 1321–1331
- 609 Hegi G. 1906. *Illustrierte Flora von Mitteleuropa. Band I - VI*. Lehmanns Verlag München:  
610 Munich, Germany
- 611 Hou J, Wang H, Fu B, Zhu L, Wang Y, Li Z. 2016. Effects of plant diversity on soil erosion  
612 for different vegetation patterns. *CATENA* **147**: 632–637. DOI:  
613 10.1016/j.catena.2016.08.019

614 Huang D, Han JG, Wu JY, Wang K, Wu WL, Teng WJ, Sardo V. 2010. Grass hedges for the  
615 protection of sloping lands from runoff and soil loss: An example from Northern  
616 China. *Soil and Tillage Research* **110**: 251–256. DOI: 10.1016/j.still.2010.08.013

617 Hussein J, Yu B, Ghadiri H, Rose C. 2007. Prediction of surface flow hydrology and  
618 sediment retention upslope of a vetiver buffer strip. *Journal of Hydrology* **338**: 261–  
619 272

620 Isselin-Nondedeu F, Bédécarrats A. 2007. Influence of alpine plants growing on steep slopes  
621 on sediment trapping and transport by runoff. *Catena*. **71**: 330–339. DOI:  
622 10.1016/j.catena.2007.02.001

623 Jauzein P, Nawrot O. 2011. *Flore d'Ile-de-France*. QUAE: Versailles, France

624 Kervroëdan L, Armand R, Saunier M, Faucon M-P. 2019. Effects of plant traits and their  
625 divergence on runoff and sediment retention in herbaceous vegetation. *Plant and Soil*  
626 **441**: 511–524. DOI: 10.1007/s11104-019-04142-6

627 Kervroëdan L, Armand R, Saunier M, Ouvry J-F, Faucon M-P. 2018. Plant functional trait  
628 effects on runoff to design herbaceous hedges for soil erosion control. *Ecological*  
629 *Engineering* **118**: 143–151. DOI: 10.1016/j.ecoleng.2018.04.024

630 Knisel WG, Nicks AD. 1980. *CREAMS: A Field Scale Model for Chemicals, Runoff, and*  
631 *Erosion from Agricultural Management Systems*. Conservation Research Report. U.S.  
632 Department of Agriculture, Science and Education Administration, 640

633 Lambinon J, Delvosalle L, Duvigneaud J. 2012. *Nouvelle flore de la Belgique, du G.-D. de*  
634 *Luxembourg, du nord de la France et des régions voisines*.

635 Lambrechts T, François S, Lutts S, Muñoz-Carpena R, Biielders CL. 2014. Impact of plant  
636 growth and morphology and of sediment concentration on sediment retention  
637 efficiency of vegetative filter strips: Flume experiments and VFSSMOD modeling.  
638 *Journal of Hydrology* **511**: 800–810. DOI: 10.1016/j.jhydrol.2014.02.030

639 Lin C, Tu S, Huang J, Chen Y. 2009. The effect of plant hedgerows on the spatial distribution  
640 of soil erosion and soil fertility on sloping farmland in the purple-soil area of China.  
641 *Soil and Tillage Research* **105**: 307–312. DOI: 10.1016/j.still.2009.01.001

642 Liu H, Yao L, Lin C, Wang X, Xu W, Wang H. 2018a. 18-year grass hedge effect on soil  
643 water loss and soil productivity on sloping cropland. *Soil and Tillage Research* **177**:  
644 12–18. DOI: 10.1016/j.still.2017.11.007

645 Liu J, Gao G, Wang S, Jiao L, Wu X, Fu B. 2018b. The effects of vegetation on runoff and  
646 soil loss: Multidimensional structure analysis and scale characteristics. *Journal of*  
647 *Geographical Sciences* **28**: 59–78. DOI: 10.1007/s11442-018-1459-z

648 Liu Y-F, Dunkerley D, López-Vicente M, Shi Z-H, Wu G-L. 2020. Trade-off between  
649 surface runoff and soil erosion during the implementation of ecological restoration  
650 programs in semiarid regions: A meta-analysis. *Science of The Total Environment*  
651 **712**: 136477. DOI: 10.1016/j.scitotenv.2019.136477

- 652 Ludwig JA, Wilcox BP, Breshears DD, Tongway DJ, Imeson AC. 2005. Vegetation patches  
653 and runoff-erosion as interacting ecohydrological processes in semiarid landscapes.  
654 *Ecology*. **86**: 288–297. DOI: 10.1890/03-0569
- 655 Mansion D, Dume G, Rameau JC. 1989. *Flore Forestière Française : Guide Ecologique*  
656 *Illustré*. Institut pour le développement forestier: Paris
- 657 Mariotte P, Mehrabi Z, Bezemer TM, De Deyn GB, Kulmatiski A, Drigo B, Veen GC, van  
658 der Heijden MG, Kardol P. 2017. Plant–Soil Feedback: Bridging Natural and  
659 Agricultural Sciences. *Trends in ecology & evolution*
- 660 Martin C, Pohl M, Alewell C, Körner C, Rixen C. 2010. Interrill erosion at disturbed alpine  
661 sites: Effects of plant functional diversity and vegetation cover. *Basic and Applied*  
662 *Ecology* **11**: 619–626. DOI: 10.1016/j.baae.2010.04.006
- 663 Maun MA. 1998. Adaptations of plants to burial in coastal sand dunes. **76**: 26
- 664 Mekonnen M, Keesstra SD, Ritsema CJ, Stroosnijder L, Baartman JEM. 2016. Sediment  
665 trapping with indigenous grass species showing differences in plant traits in northwest  
666 Ethiopia. *Catena* **147**: 755–763. DOI: 10.1016/j.catena.2016.08.036
- 667 Mekonnen M, Keesstra SD, Stroosnijder L, Baartman JEM, Maroulis J. 2015. Soil  
668 Conservation Through Sediment Trapping: A Review. *Land Degradation &*  
669 *Development* **26**: 544–556. DOI: 10.1002/ldr.2308
- 670 Meyer LD, Dabney SM, Harmon WC. 1995. Sediment-trapping effectiveness of stiff-grass  
671 hedges. *American Society of Agricultural Engineers* **38**: 809–815
- 672 Morgan RPC. 2004. Vegetative-Based Technologies for Erosion Control. In: Stokes A,  
673 Spanos I, Norris JE and Cammeraat E (eds) *Eco- and Ground Bio-Engineering: The*  
674 *Use of Vegetation to Improve Slope Stability*. Springer: Dordrecht, The Netherlands,  
675 265–272
- 676 Morgan RPC. 2009. *Soil Erosion and Conservation*. John Wiley & Sons
- 677 Morgan RPC, Duzant JH. 2008. Modified MMF (Morgan–Morgan–Finney) model for  
678 evaluating effects of crops and vegetation cover on soil erosion. *Earth Surface*  
679 *Processes and Landforms* **33**: 90–106. DOI: 10.1002/esp.1530
- 680 Mouillot D, Villéger S, Scherer-Lorenzen M, Mason NWH. 2011. Functional Structure of  
681 Biological Communities Predicts Ecosystem Multifunctionality. *PLoS ONE* **6**:  
682 e17476. DOI: 10.1371/journal.pone.0017476
- 683 Muñoz Carpena R, Parsons JE. 2014. *VFSMOD - Vegetative filter strips modelling system*.  
684 Model documentation and user's manual. University of Florida, 176
- 685 Podwojewski P, Janeau JL, Grellier S, Valentin C, Lorentz S, Chaplot V. 2011. Influence of  
686 grass soil cover on water runoff and soil detachment under rainfall simulation in a  
687 sub-humid South African degraded rangeland. *Earth Surface Processes and*  
688 *Landforms* **36**: 911–922. DOI: 10.1002/esp.2121

689 Poesen J. 2018. Soil erosion in the Anthropocene: Research needs. *Earth Surface Processes*  
690 *and Landforms* **43**: 64–84. DOI: 10.1002/esp.4250

691 Pohl M, Alig D, Körner C, Rixen C. 2009. Higher plant diversity enhances soil stability in  
692 disturbed alpine ecosystems. *Plant and Soil* **324**: 91–102. DOI: 10.1007/s11104-009-  
693 9906-3

694 Puigdefábregas J. 2005. The role of vegetation patterns in structuring runoff and sediment  
695 fluxes in drylands. *Earth Surface Processes and Landforms* **30**: 133–147. DOI:  
696 10.1002/esp.1181

697 Remy J-C, Le Bissonnais Y. 1998. *Comparaison des phénomènes d'érosion entre le nord et*  
698 *le sud de l'Europe : ampleur des problèmes et nature des mécanismes*. Bulletin réseau  
699 érosion. IRD: Montpellier

700 Renschler C, Flanagan D, Engel B, Frankenberger J. 2002. *GeoWEPP-The Geo-spatial*  
701 *interface for the Water Erosion Prediction Project*. . DOI: 10.13031/2013.10418

702 Rey F, Labonne S. 2015. Resprout and survival of willow (*Salix*) cuttings on bioengineering  
703 structures in actively eroding gullies in marls in a mountainous Mediterranean  
704 climate: A large-scale experiment in the Francon catchment (southern Alps, France).  
705 *Environmental Management* **56**: 971–983. DOI: 10.1007/s00267-015-0542-9

706 Richet J-B, Ouvry J-F, Saunier M. 2017. The role of vegetative barriers such as fascines and  
707 dense shrub hedges in catchment management to reduce runoff and erosion effects:  
708 Experimental evidence of efficiency, and conditions of use. *Ecological Engineering*  
709 **103**: 455–469. DOI: 10.1016/j.ecoleng.2016.08.008

710 Rothmaler W, Jäger EJ. 2009. *Rothmaler - Exkursionsflora von Deutschland. Bd. 3:*  
711 *Gefäßpflanzen: Atlasband*. Spektrum Akademischer Verlag: Berlin, Germany

712 Stokes A (ed). 2007. *Eco- and ground bio-engineering: the use of vegetation to improve*  
713 *slope stability: proceedings of the First International Conference on Eco-*  
714 *Engineering, 13-17 September 2004*. Springer: Dordrecht

715 Stokes A, Douglas GB, Fourcaud T, Giadrossich F, Gillies C, Hubble T, Kim JH, Loades  
716 KW, Mao Z, McIvor IR, Mickovski SB, Mitchell S, Osman N, Phillips C, Poesen J,  
717 Polster D, Preti F, Raymond P, Rey F, Schwarz M, Walker LR. 2014. Ecological  
718 mitigation of hillslope instability: ten key issues facing researchers and practitioners.  
719 *Plant and Soil*. **377**: 1–23. DOI: 10.1007/s11104-014-2044-6

720 Styczen ME, Morgan RPC. 1995. Engineering properties of vegetation. In: Morgan RPC and  
721 Rickson RJ (eds) *Slope Stabilization and Erosion Control: A Bioengineering*  
722 *Approach*. E & FN SPON: London, 4–60

723 Temple DM, Robinson KM, Ahring RM, Davis AG. 1987. *Stability Design of Grass-Lined*  
724 *Open Channels*. U.S. Department of Agriculture: Washington, D.C.

725 Tilman D. 1999. The ecological consequences of changes in biodiversity: A search for  
726 general principles. *Ecology* **80**: 1455–1474. DOI: 10.1890/0012-  
727 9658(1999)080[1455:TECOCI]2.0.CO;2

- 728 Tilman D. 2001. Functional Diversity. In: Levin SA (ed) *Encyclopedia of Biodiversity*.  
729 Elsevier: New York, 109–120. DOI: 10.1016/B0-12-226865-2/00132-2
- 730 Tilman D, Isbell F, Cowles JM. 2014. Biodiversity and Ecosystem Functioning. *Annual*  
731 *Review of Ecology, Evolution, and Systematics* **45**: 471–493. DOI: 10.1146/annurev-  
732 ecolsys-120213-091917
- 733 Tomer MD, Dosskey MG, Burkart MR, James DE, Helmers MJ, Eisenhauer DE. 2008.  
734 Methods to prioritize placement of riparian buffers for improved water quality.  
735 *Agroforest Syst*: 10 p.
- 736 Turnbull L, Wainwright J, Brazier RE. 2008. A conceptual framework for understanding  
737 semi-arid land degradation: ecohydrological interactions across multiple-space and  
738 time scales. *Ecohydrology* **1**: 23–34. DOI: 10.1002/eco.4
- 739 Université de Bourgogne (UFR Science de la vie). 2018. *Nouvelle Flore de Bourgogne -*  
740 *Tome II Clés de détermination. Flore de Bourgogne*
- 741 Van Dijk PM, Kwaad FJPM, Klapwijk M. 1996. Retention of water and sediment by grass  
742 strips. *Hydrological Processes* **10**: 1069–1080. DOI: 10.1002/(SICI)1099-  
743 1085(199608)10:8<1069::AID-HYP412>3.0.CO;2-4
- 744 Vandaele K, Poesen J. 1995. Spatial and temporal patterns of soil erosion rates in an  
745 agricultural catchment, central Belgium. *CATENA* **25**: 213–226. DOI: 10.1016/0341-  
746 8162(95)00011-G
- 747 Vannoppen W, Vanmaercke M, De Baets S, Poesen J. 2015. A review of the mechanical  
748 effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews* **150**:  
749 666–678. DOI: 10.1016/j.earscirev.2015.08.011
- 750 Vieira DAN, Dabney SM. 2012. Two-dimensional flow patterns near contour grass hedges.  
751 *Hydrological Processes* **26**: 2225–2234. DOI: 10.1002/hyp.8262
- 752 Villarroel B. 2015. Influence des traits morphologiques des végétaux herbacés sur l'érosion et  
753 le ruissellement des sols cultivés du nord-ouest de l'Europe. MSc Thesis,  
754 AgoParisTech
- 755 Violle C, Navas M-L, Vile D, Kazakou E, Fortunel C, Hummel I, Garnier E. 2007. Let the  
756 concept of trait be functional! *Oikos* **116**: 882–892. DOI: 10.1111/j.2007.0030-  
757 1299.15559.x
- 758 Williams RD, Nicks AD. 1988. Using CREAMS to simulate filter strip effectiveness in  
759 erosion control. *Journal of Soil and Water Conservation* **43**: 108–112
- 760 Wu JY, Huang D, Teng WJ, Sardo VI. 2010. Grass hedges to reduce overland flow and soil  
761 erosion. *Agronomy for Sustainable Development* **30**: 481–485. DOI:  
762 10.1051/agro/2009037
- 763 Xiao B, Wang Q, Wang H, Wu J, Yu D. 2012. The effects of grass hedges and micro-basins  
764 on reducing soil and water loss in temperate regions: A case study of Northern China.  
765 *Soil and Tillage Research* **122**: 22–35. DOI: 10.1016/j.still.2012.02.006

766 Yuan Y, Bingner RL, Locke MA. 2009. A Review of effectiveness of vegetative buffers on  
767 sediment trapping in agricultural areas. *Ecohydrology* **2**: 321–336. DOI:  
768 10.1002/eco.82

769 Zhang L, Wang J, Bai Z, Lv C. 2015. Effects of vegetation on runoff and soil erosion on  
770 reclaimed land in an opencast coal-mine dump in a loess area. *CATENA* **128**: 44–53.  
771 DOI: 10.1016/j.catena.2015.01.016

772 Zhu H, Fu B, Wang S, Zhu L, Zhang L, Jiao L, Wang C. 2015. Reducing soil erosion by  
773 improving community functional diversity in semi-arid grasslands. *Journal of Applied*  
774 *Ecology* **52**: 1063–1072. DOI: 10.1111/1365-2664.12442

775 Zuo X, Zhang J, Lv P, Zhou X, Li Y, Luo Y, Luo Y, Lian J, Yue X. 2016. Plant functional  
776 diversity mediates the effects of vegetation and soil properties on community-level  
777 plant nitrogen use in the restoration of semiarid sandy grassland. *Ecological*  
778 *Indicators* **64**: 272–280. DOI: 10.1016/j.ecolind.2016.01.012

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

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

Family	Species name	Life form	Minimum vegetative height (cm)
Adoxaceae	<i>Sambucus ebulus</i> L.	Hem.	55 (50; 80)
Apiaceae	<i>Anthriscus sylvestris</i> (L.) Hoffmann	Hem.	45 (40; 80)
	<i>Bupleurum falcatum</i> L.	Hem.	30 (20; 50)
	<i>Heracleum sphondylium</i> L.	Hem.	50 (30; 50)
Asteraceae	<i>Achillea ptarmica</i> L.	Hem.	20 (20; 30)
	<i>Artemisia verlotiorum</i>	Hem.	70 (67.5; 150)
	<i>Artemisia vulgaris</i> L.	Hem.	60 (52.5; 60)
	<i>Aster laevis</i> L.	Hem.	60 (60; 60)
	<i>Aster salignus</i> Willd.	Hem.	80 (72.5; 90)
	<i>Eupatorium cannabinum</i> L.	Hem.	55 (50; 80)
	<i>Hieracium piloselloides</i> Vill.	Hem.	20 (20; 20)
	<i>Senecio jacobaea</i> L.	Hem.	30 (30; 40)
	<i>Tanacetum corymbosum</i> L.	Hem.	30 (30; 50)
	<i>Tanacetum parthenium</i> L.	Hem.	30 (30; 30)
	<i>Tanacetum vulgare</i> L.	Hem.	55 (42.5; 60)
Caryophyllaceae	<i>Saponaria officinalis</i> L.	Hem.	30 (30; 30)
Clusiaceae	<i>Hypericum perforatum</i> L.	Hem.	27.5 (21.25; 30)
Cyperaceae	<i>Carex acutiformis</i> Ehrh.	Hem.	50 (35; 50)
	<i>Carex binervis</i> Smith	C. Hem.	30 (30; 30)
	<i>Carex brizoides</i> L.	Hem.	25 (25; 30)
	<i>Carex canescens</i> L.	Hem.	20 (20; 25)
	<i>Carex otrubae</i> Podp.	Hem.	30 (30; 30)
	<i>Carex diandra</i> Schrank	Hem.	20 (20; 30)
	<i>Carex distans</i> L.	Hem.	22.5 (20; 30)
	<i>Carex divulsa</i> Stokes	C. Hem.	20 (20; 30)
	<i>Carex elongata</i> L.	C. Hem.	30 (30; 30)
	<i>Carex flacca</i> Schreb.	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</i> (Lam.) Beauv.	Hem.	20 (20; 45)
	<i>Melica ciliata</i> L.	Hem.	22.5 (20; 30)
	<i>Melica nutans</i> L.	Hem.	30 (22.5; 30)
	<i>Melica uniflora</i> Retz.	Hem.	25 (20; 30)
	<i>Milium effusum</i> L.	Hem.	55 (50; 80)
	<i>Phalaris arundinacea</i> L.	Hem.	50 (50; 80)
Rosaceae	<i>Filipendula ulmaria</i> (L.) Maxim.	R. Hem.	50 (50; 100)

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

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

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