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

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ABSTRACT

Vegetation controls concentrated runoff and erosion in the European loess belt by increasing hydraulic roughness and sediment retention. Studies of plant effects on runoff velocity are usually based on a taxonomical characterisation and do not consider the effects of aboveground plant functional traits in attempts to understand soil erosion by water. This trait-based plant study investigates aboveground plant functional trait effects of herbaceous hedges on the hydraulic roughness to understand soil erosion. Eight aboveground morphological traits were measured on fourteen indigenous and perennial plant species (caespitose or comprising dry biomass in winter) from north-west Europe with a high morphological variability. For each trait, density-weighted traits were calculated. The effects of traits and density-weighted traits were examined using a runoff simulator with four discharges. The leaf density and area, as well as density-weighted stem and leaf areas, stem diameter and specific leaf area were positively correlated with the hydraulic roughness. Generalised linear models defined the best combinations of traits and density-weighted traits: (1) leaf density and leaf area, (2) density-weighted leaf area and density-weighted projected stem area, and (3) density-weighted leaf area and density-weighted stem diameter. Moreover, the effects of leaf density, leaf area and density-weighted specific leaf area, varied depending on the discharge. This study is one of the first characterisation of aboveground trait effects on hydraulic roughness and highlights that vegetation with large stem density, diameter and leaf area plays a significant role in minimising soil erosion. The selection of plant species can derive from these plant trait effects to design reconstructed herbaceous hedges to minimise soil erosion.

1. Introduction

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

The effects of herbaceous vegetation on runoff and soil erosion have been studied over the past decades (Haan et al., 1994; Lambrechts et al., 2014; Ludwig et al., 2005; Temple et al., 1987). Blanco-Canqui et al. (2006), Dosskey et al. (2010), Lambrechts et al. (2014), Le Bissonnais et al. (2005), Ruiz-Colmenero et al. (2013) and Stokes et al. (2014) noted the direct effects of vegetation cover on splash

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

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

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

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

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

2. Materials and methods

2.1. Plant materials

Fourteen plant species that display contrasting aboveground morphological traits were chosen from 76 candidate species, resulting in six filters of selected functional types involved in the mitigation of soil erosion in north-west Europe applied to the 3500 spermatophyte species from north-west Europe (Lambinon et al., 2012). These selective filters were as follows: (1) Raunkiaer's life-form categories of "herbaceous chamaephytes", "hemicryptophytes" and "geophytes", i.e., perennial herbaceous vegetation that provide an effective soil cover during all seasons; (2) the presence of fresh (i.e., herbaceous chamaephytes and caespitose hemicryptophytes) or dry (i.e., non-caespitose hemicryptophytes and geophytes) biomass in winter when soil erosion is observed in north-west Europe (Boardman and Poesen, 2006); (3) the presence of rhizomes or stolon to ensure lateral spreading capacity and burying tolerance due to sediment deposition; (4) vegetative height ≥ 20 cm, as it is the water maximal level in the catchment in north-west Europe; (5) a broad ecological niche to select species able to grow in several silty agricultural soils; and (6) non-weed species to prohibit their expansion in agricultural territories of north-west Europe.

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

2.2. Plant morphological trait measurements

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