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REGULAR ARTICLE

Plant functional traits and species ability for sediment retention during concentrated flow erosion

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Abstract
Background and aims Plant species can have a major effect on erosion dynamics and soil losses by retaining sediment transported during concentrated runoff. Identifying plant functional traits that influence and predict a species ability for sediment trapping is therefore of great interest, especially to improve management and restoration of degraded lands.
Methods Sediment trapping ability of four morphologically contrasted species, the broadleaf species *Buxus sempervirens* and *Lavandula angustifolia*, and the coniferous species *Juniperus communis* and *Pinus nigra*, were investigated with flume experiments. Six functional traits describing stem, leaf and the overall plant morphology, were measured on seedlings. Analyses were performed to compare species efficiency in sediment trapping and to identify traits related to the amount of sediment trapped.
Results Sediment trapping (RTS) was the highest upslope of *Lavandula* and the lowest upslope of *Juniperus*. Principal component analysis showed that RTS was best correlated (positively) with canopy density, described by plant biomass and leaf area per unit volume of plant. Leaf area and plant roundness were also positively related to RTS but to a lesser extent.
Conclusions The results of this experimental study suggest that canopy completeness, leaf morphology and plant shape influence sediment retention by plants. Such knowledge may improve the diagnosis of land vulnerability to erosion and the prediction of ecosystem functioning after ecological restoration by the construction of bioengineering works in gully floors.

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Keywords Leaf morphology · Concentrated runoff · Plant functional trait · Sediment trapping · Flume experiment · Gully erosion · Restoration

Introduction

Soil erosion and soil loss are natural processes that have been intensified with human land use, and rank as main environmental issues in many cultivated and natural lands (Morgan 1995; Pimentel et al. 1995;

Pimentel and Kounang 1998). Erosion control and sediment retention have been listed among the 17 major ecosystem services contributing to human welfare and development (Costanza et al. 1997; de Groots et al. 2002), but also belong to those services that have degraded during the last sixty years, threatening people economical and physical safety (Millennium Ecosystem Assessment 2005).

In Southern Alps in France, gully erosion on very erodible marly soils has led to the formation of extensive degraded areas called badlands (Oostwoud Wijdenes and Ergenzinger 1998; Poesen et al. 2003), in which high rates of soil loss have been observed (Mathys et al. 2003). Therefore, these eroded lands, which are now subjected to rigorous management, often need ecological restoration (Rey 2009). In recent years, ecological engineering solutions have developed and promote the use of vegetation to protect soils and prevent water erosion (Norris et al. 2008; Stokes et al. 2010).

Indeed, vegetation has many effects on erosion control and soil stability (Thornes 1990), that can be divided into two main categories: active and passive protection. On the one hand, active protection encompasses all the processes, hydrological as well as mechanical, that affect soil erodibility and reduce erosion rates. Plant canopy reduces surface runoff and erosion rates by intercepting rainfall, and by increasing water infiltration and surface roughness (Styzcen and Morgan 1995). Plant roots lower pore water pressure, increase soil aggregate stability and provide additional soil cohesion through root reinforcement (Gyssels et al. 2005). On the other hand, passive protection processes do not prevent erosion from occurring but reduce soil loss at a larger scale (i.e. slope) by locally enhancing sediment deposition (Descheemaeker et al. 2006) upslope of plants and forming phytogenic mounds that act as filtering barriers (Bergkamp 1998; Sanchez and Puigdefábregas 1994). These vegetative filters have been extensively studied for their role in reducing water pollution with sediment and nutrient near croplands (Magette et al. 1989; Robinson et al. 1996; Abu-Zreig et al. 2004) and riparian areas (Daniels and Gilliam 1993; Lee et al. 2000; Hook 2003).

The use of plant functional traits to relate plant species to their environment and to predict species effect on ecosystem functioning has received a growing interest over recent years (Lavorel and Garnier 2002; Lavorel et al. 2007). Recent conceptual advances suggest that functional effect traits play a major role in ecosystem processes (Chapin et al. 2000; Lavorel and Garnier 2002), and several authors highlight the need to identify plant traits that contribute to the provision of ecological services when focusing on ecological restoration of ecosystems (Díaz et al. 2006; Luck et al. 2009). Many studies have been carried out to better understand the role of plant traits in biogeochemical cycles (e.g. Cornelissen et al. 1999; Craine et al. 2002; Cornwell et al. 2008; De Deyn et al. 2008), response to fire (Lavorel and Garnier 2002; Pausas et al. 2004) or grazing (Saatkamp et al. 2010), but little is known about the effect of plant traits on erosion dynamics.

Despite the well-known potential effect plants can have on erosion processes in the ecosystem, to date, few studies have focused interest on plant morphological traits influencing sediment trapping. In the case of grass filter strips, filter length and width appeared as important features for sediment retention (Van Dijk et al. 1996; Lee et al. 2000; Abu-Zreig et al. 2004). At the scale of the individual plant species, Bochet et al. (2000) found that canopy density (i.e. number of stems) of shrubs and grasses from semi-arid environments influenced the height of phytogenic mounds. Isselin-Nondedeu and Bédécarrats (2007) also showed that sediment trapping was positively correlated with canopy density but negatively with plant roundness index (plant width to length ratio) of alpine species from mountain ecosystems. Therefore, comparing and predicting species efficiency for sediment trapping using plant traits requires expanding our data base. In particular, to our knowledge, leaf morphology has never been considered in experimental studies on the relationship between plant traits and sediment trapping.

In this study, our objectives were (1) to investigate the ability for sediment trapping of woody species typical of marly eroded lands and (2) to identify functional traits that best explain this ability. Sediment trapping was evaluated at the plant scale during flume experiments carried out on four nursery-grown species prevalent in eroded marly ecosystems of the French Southern Alps. We used one-year old individuals to study soil retention processes at the early stages of natural vegetation colonization, when vegetation cover is still low and mainly composed of seedlings, but when its role in erosion control

Table 1 Mean size (canopy height; length, in the direction of the flow; and width, perpendicular to the flow; cm ± SE) and mean interception volume at 1 cm height (cm^3 ± SE) of the seedlings tested

	Height	Length	Width	Interception volume
Juniperus	48.9±0.8	14.5±0.7	15.2±0.6	52.4±9.1
Pinus	15.8±0.5	14.4±1.0	16.1±0.9	88.1±15.9
Buxus	21.0±0.6	15.9±1.0	17.2±1.1	24.9±3.5
Lavandula	9.1±0.7	6.6±0.4	7.4±0.4	15.2±1.8

processes is already crucial. This represents one of the first attempts, to our knowledge, to analyse vegetation ability to trap sediments at the plant scale in laboratory conditions. Six traits related to plant, leaf and stem morphology, and selected for their alleged influence on sediment trapping, were examined. Analyses were performed to compare species ability to trap sediments and to identify functional traits involved in sediment retention, for a future use of species which will have maximal sediment trapping effects in bioengineering works.

Materials and methods

Plant material

For this study, four species growing spontaneously in eroded marly lands of the French Southern Alps were chosen: two broadleaf species, *Buxus sempervirens* and *Lavandula angustifolia* (hereafter *Buxus* and *Lavandula*), and two conifers, *Pinus nigra austriaca*, used in the past for soil stabilization (Vallauri et al. 2002), and *Juniperus communis* (hereafter *Pinus* and *Juniperus*). One-year old individuals of each species were obtained from a nursery. These four species presented different above-ground morphology. The two conifers have thin needles (approximately 0.1 cm large) but *Juniperus*' ones are shorter than *Pinus*' ones (1 and 2–5 cm, respectively, on average). On the other hand, the broadleaf species present different leaf morphologies, *Buxus* having oval leaves and *Lavandula* having rather linear leaves (approximately 1.5×0.5 cm and 2×0.3 cm, respectively). As a result of their growth in a nursery under non limiting conditions, seedlings height ranged from 9.1 cm for *Buxus* to 48.9 cm for *Juniperus* (Table 1), and seedlings diameter was about 7 cm for *Lavandula* and about 15 cm for other species.

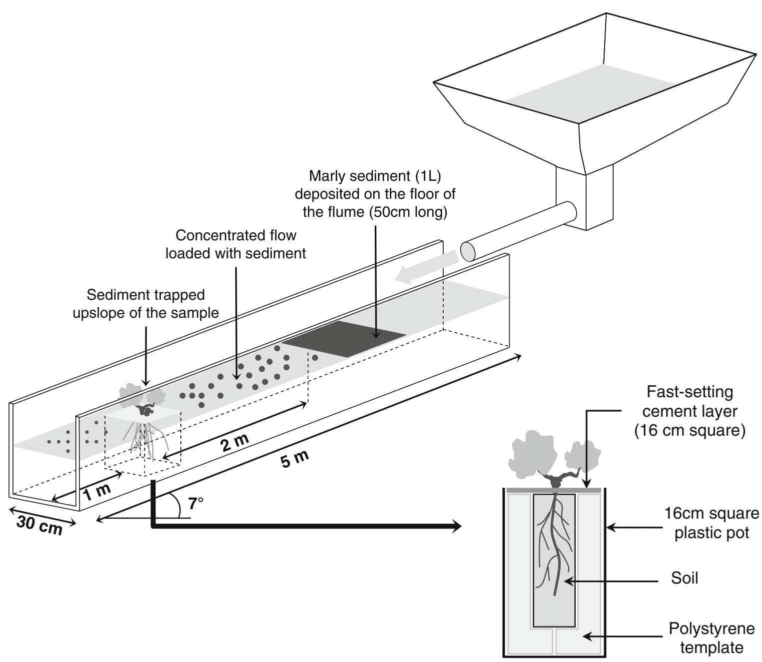

Fig. 1 Schematic diagram of the hydraulic flume (flume modified and adapted after Poesen et al. 1999) during sediment trapping tests

Hydraulic flume experiment

Prior to the flume experiments, plants were placed in 16 cm square plastic pots using a polystyrene template to ensure they were positioned correctly in the pot (Fig. 1). A thin layer of fast-setting cement was then applied on the whole soil surface to the upper rim of the pot. This was done to homogenise the soil surface between samples in order to exclude a possible detachment of soil particles during the tests and to restrict the observations to the sediment trapping of above-ground parts of plants only.

Before each test, pots were placed in an opening box at the bottom of a 5 m-long plexiglass flume (Fig. 1), similar to the one used by Poesen et al. (1999) but modified and adapted to the present objectives. Adhesive tape was stuck straddling the rims of the pot and the bottom of the flume to prevent edge effects. Marly sediment collected in the field (Draix experimental site, Alpes-de-Haute-Provence, France, 44°08′N, 6°20′E) was sieved (1 cm mesh) and dried to ensure similar granulometry and moisture during the tests. One litre of marly sediment was regularly spread over a 50 cm distance, two meters upslope of the plant sample (Fig. 1). Twenty samples per species (single plant one at a time) were then exposed to concentrated flow at a constant discharge (Q) of 0.0005 $m^3.s^{-1}$ during 60 s. During the tests, all the sediments were progressively carried along with the flow and filtered by the plant (Fig. 2).

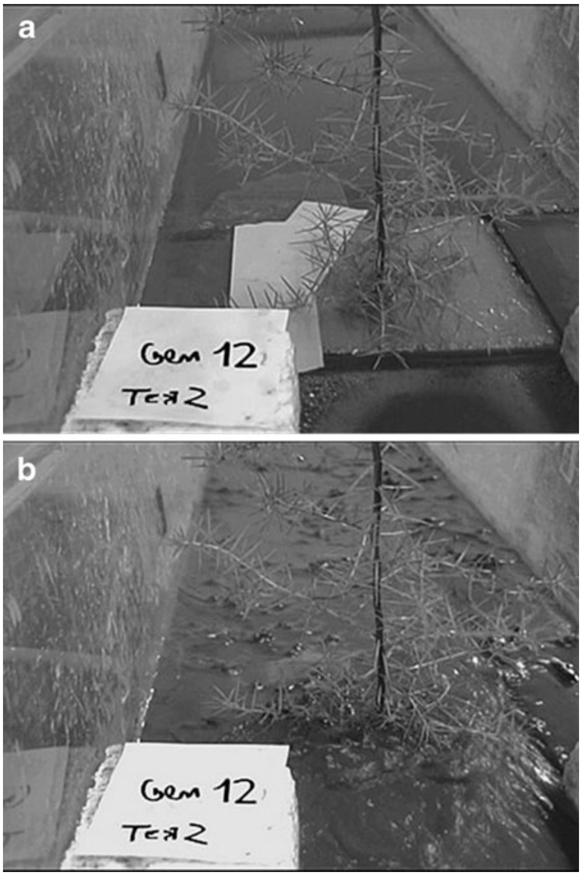

Fig. 2 Pictures of a *Juniperus* sample submitted to concentrated flow loaded with sediment in the experimental flume. Pictures represent the sample **a** before and **b** during the test

Sediment trapping

After the tests, sediment trapped by the plant was collected on the cement layer, oven-dried (48 h at 72°C) and weighed. Plant width (perpendicular to the flow) and length (direction of the flow), both at 1 cm height (maximum flow height observed), were measured to calculate interception volume (Table 1). Relative trapped sediment (RTS, $g.cm^{-3}$) was calculated as the mass of sediment trapped per unit volume. Plants were then harvested for trait measurements.

Trait measurements

After each test, a set of plant traits, *a priori* directly or indirectly related to sediment trapping were measured. A plant roundness index was calculated as the ratio of width to length to investigate the effect of plant shape. Roundness index values of 1 indicate circular shapes, values greater than 1 indicate plants larger in width than in length and vice versa for values below 1. Mean leaf area was estimated on five to ten fresh leaves per plant at a time. To evaluate plant roughness towards concentrated flow, we calculated leaf area per unit volume by dividing leaf area (mean leaf area x leaf number in the interception volume) by the interception volume. Mean leaf dry matter content (LDMC, $mg.g^{-1}$) was determined for each plant, using the same leaf samples as for mean leaf area estimation. LDMC was calculated by dividing leaf oven-dry mass (48 h at 72°C) by leaf fresh mass. Stem specific density (SSD, $mg.mm^{-3}$) was calculated as the ratio of the oven-dry mass of a section of the plant's stem to its volume, measured manually with a calliper when still fresh. LDMC and SSD were used as estimations of plant resistance to mechanical

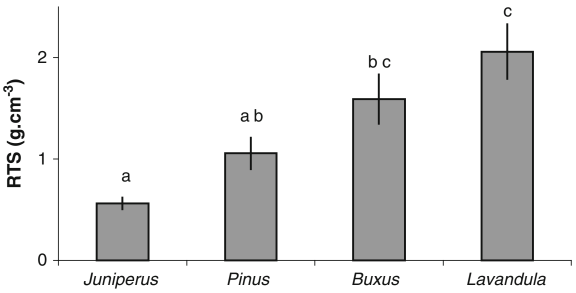

Fig. 3 Differences in sediment trapping ability among the four species studied. Bars are means ± SE. Different letters indicate significant differences among species (Tukey's HSD test, α= 0.05). RTS: amount of trapped sediment

constraints related to concentrated flow (Cornelissen et al. 2003). Total plant dry mass was then weighed and normalized by canopy volume (as it is plant-size dependent) to obtain dry mass per unit volume and allow biomass comparisons between species.

Data analysis

A comparative approach was first used with analysis of variance (ANOVA) to determine differences in plant morphology between species and to examine differences in species ability for sediment trapping (Tukey's HSD test). Before analysis, all data were tested for normality (Shapiro-Wilk test) and corrected when needed either with logarithmic or square-root transformations. To determine how functional traits and RTS were related across species, principal components analysis (PCA) was performed on untransformed data.

Analyses were carried out with STATISTICA (version 8.0 for Windows Statsoft 1984).

Results

Species efficiency in sediment trapping

Sediment deposition was observed upslope and within the canopy of each sample, with sediment mass ranging from 12 to 230 g. The raw mass of sediment trapped ranged from 0.8% to 15% of marly sediment transported during the tests. When normalised by interception volume, results show significant RTS differences between species (Fig. 3). Broadleaf species *Lavandula* and *Buxus* trapped the highest amount of sediment per unit volume ahead of the conifers *Pinus* and *Juniperus* (ANOVA: F=10.6, p< 0.001). *Lavandula* and *Buxus* trapped respectively 3.7 and 2.8 times more sediment than *Juniperus*, and 1.9 and 1.5 times more sediment than *Pinus*.

Trait differences between species

All traits except plant roundness index showed large variation among species (Table 2). *Buxus* had the largest leaves and *Juniperus* the smallest ones, representing significant differences in leaf shapes. LDMC differences indicate that *Buxus* and *Pinus* had the tenderest leaves, as indicated by low values, while on the other hand, *Lavandula* and *Juniperus*, with high LDMC, had tougher ones. Similarly, *Buxus* had the highest SSD values ahead of *Lavandula*, *Juniperus* and *Pinus*. Finally, canopy density, described by plant dry mass and leaf area per unit volume, also differed significantly among species, *Lavandula* having the highest biomass density (dry mass per unit volume). For leaf area per unit volume, results showed that *Buxus* and *Lavandula* had significantly

Table 2 Mean values ± SE of traits for the four species studied, and results of one-way ANOVA (Statistic test F). Levels of significance are: ns non significant, *** p<0.001. Different letters indicate significant differences (Tukey's HSD test) among species

	Juniperus	*Pinus*	*Buxus*	*Lavandula*	ANOVA
Roundness (−)	1.10±0.07	1.14±0.05	1.13±0.1	1.19±0.08	0.2 ns
Mean leaf area (cm²)	$0.17{\pm}0.01^{c}$	$0.56{\pm}0.02^{b}$	$1.75{\pm}0.05^{a}$	$0.56{\pm}0.03^{b}$	419.6***
LDMC (mg.g^{-1})	$483.1{\pm}14.4^{a}$	$321.4{\pm}18.4^{b}$	$343.7{\pm}19.2^{b}$	$436.5{\pm}28.4^{a}$	14.0***
SSD (mg.mm^{-3})	$0.66{\pm}0.01^{ab}$	$0.43{\pm}0.01^{c}$	$0.73{\pm}0.01^{a}$	$0.63{\pm}0.05^{b}$	22.8***
Biomass per unit volume (mg.mm^{-3})	$0.47{\pm}0.03^{b}$	$0.96{\pm}0.08^{b}$	$0.55{\pm}0.04^{b}$	$3.37{\pm}0.4^{a}$	45.6***
Leaf area per unit volume (cm².cm^{-3})	$0.18{\pm}0.02^{c}$	$0.13{\pm}0.03^{c}$	$0.87{\pm}0.15^{a}$	$0.51{\pm}0.08^{b}$	26.7***

higher leaf area density near the soil surface than *Pinus* and *Juniperus*.

Relationship between sediment trapping and functional traits

PCA results indicate that principal component axes one, two and three explained 30.9, 23.5 and 18.3% of the variation in the database respectively. Axis one differentiated species according to leaf area per unit of interception volume and mean leaf area (Fig. 4a and b). *Lavandula* and *Buxus*, which had respectively high canopy density and large leaves, occupied the upper end of axis one, whereas *Pinus* and *Juniperus* had opposite morphologies. Axis two and three were mostly defined respectively by LDMC and SSD, and by biomass per unit volume and plant roundness. Sediment trapping ability (RTS) contributed mainly to axes one and three. Pearson's correlations (Table 3) showed that RTS was significantly positively correlated with four morphological traits. Strongest correlations appeared with leaf area per unit volume and biomass per unit volume. Mean leaf area and plant roundness were also correlated with RTS but correlation coefficients were lower. Pairwise correlation coefficient showed that several traits were significantly related. Most obviously, LDMC and SSD, describing tissue density were also positively correlated.

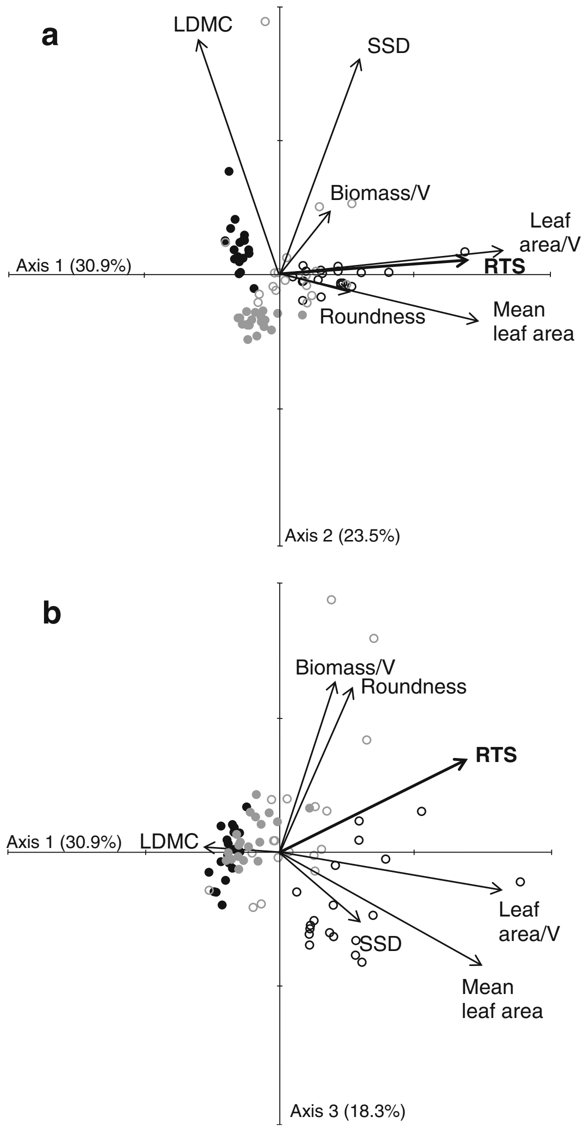

Fig. 4 Principal component axes 2 (**a**) and 3 (**b**) plotted vs axis 1 (●: *Juniperus*, ●: *Pinus*, ○: *Buxus*, ○: *Lavandula*). RTS: amount of trapped sediment; V: plant volume; SSD: stem specific density; LDMC: leaf dry matter content

Discussion

The formation of phytogenic mounds under isolated plants has been described in many degraded ecosystems (Sanchez and Puigdefabregas 1994; Bergkamp 1998; Bochet et al. 2000; El-Bana et al. 2003; Isselin-Nondedeu and Bédécarrats 2007), but we know little about functional traits influencing mound size and shape at the plant scale. The results of the present study showed that all individuals tested retained sediment during concentrated flow, but there were important differences between species effectiveness as found in previous studies (Bochet et al. 2000; Isselin-Nondedeu and Bédécarrats 2007). *Lavandula* and *Juniperus* were found the most and least effective species respectively, and higher RTS were obtained upslope of the two broadleaf species. The raw mass of sediment trapped was much lower than sediment discharge reductions observed in previous laboratory experiments (e.g. up to 90% of coarse particles in Meyer et al. 1995; from 50 to 99% in Van Dijk et al. 1996). Differences in experimental settings, like plant filter size, experiment duration, flume slope, soil type or the way water was loaded with sediment, may explain these differences. Moreover, by recovering the soil of the samples by a thin layer of cement, we may reduce surface roughness and thus sediment deposition rates.

Table 3 Correlation matrix between functional traits and sediment trapping ability (RTS). Indicated data correspond to correlation coefficient r and significance levels (**p*<0.05; ***p*<0.01; ****p*<0.001). LDMC: leaf dry matter content; SSD: stem specific density

	RTS	Roundness	Mean leaf area	LDMC	SSD	Biomass per unit volume	Leaf area per unit volume
RTS ($g.cm^{-3}$)	1	–	–	–	–	–	–
Roundness (−)	0.26*	1	–	–	–	–	–
Mean leaf area (cm^2)	0.25*	0.03	1	–	–	–	–
LDMC ($mg.g^{-1}$)	−0.06	−0.09	−0.36***	1	–	–	–
SSD ($mg.mm^{-3}$)	0.09	−0.006	0.27*	0.58***	1	–	–
Biomass per unit volume ($mg.mm^{-3}$)	0.39***	0.21	−0.18	0.13	−0.02	1	–
Leaf area per unit volume ($cm^2.cm^{-3}$)	0.52***	0.06	−0.58***	−0.09	0.28*	0.10	1

This study focused on raw mass of sediment without distinguishing particle size and mound composition (i.e. silt and clay content). Soil erosion and sediment deposition are processes strongly related to particle size, fine clay particles being preferentially detached from source area and coarse particles being the first to deposit. Meyer et al. (1995) have shown that sediment retention decreased as particle size decreased, most of the sediment trapped being coarser than 125 μm. Therefore, particle size distribution in the sediment deposited upslope of plants could be an important parameter to consider.

Differences in RTS between species suggest that leaf and whole plant morphologies are important determinants of sediment retention ability. Multivariate analysis showed that species ability for sediment retention was significantly related to several plant features. The strongest relationship was found with canopy density, defined either by plant biomass or leaf area per unit volume. The more the vegetation foliage is dense, the more sediment is trapped. This conclusion is consistent with previous investigations which highlighted that canopy density and completeness determined sediment trapping ability (Van Dijk et al. 1996; Bochet et al. 2000; Isselin-Nondedeu and Bédécarrats 2007).

Leaf area also played an important role in sediment retention, larger leaves providing larger interception area and thus increasing sediment trapping ability. No significant correlation was found between RTS and LDMC or SSD. These two traits describe tissue density and are often used as surrogates for resistance to physical hazards and abiotic factors (Cornelissen et al. 2003). Yet, during the tests, we observed that the stems of *Juniperus* bended under concentrated flow. This suggests that stem resistance to bending could affect species effectiveness in sediment trapping and it could be an additional reason to explain the low RTS values this species presented. Measurements of species biomechanical properties directly related to plant resistance to external constraints, such as leaf tensile strength (e.g. Díaz et al. 2001), stem bending resistance (e.g. Goodman and Ennos 1997), lignin and cellulose content (Genet et al. 2005) or resistance to uprooting by concentrated flow (e.g. Burylo et al. 2009) should be included in future experiments.

Plant shape also affected sediment trapping ability. High roundness indices, which define plants wider than long, were associated with higher mass of trapped sediment. This result is consistent with previous investigations which highlighted the efficiency in sediment retention of plants growing perpendicular to the slope and forming a barrier to the flow (Valentin et al. 1999; Bochet et al. 2000; Abu-Zreig et al. 2004), even if Isselin-Nondedeu and Bédécarrats (2007) found inverse relationship between sediment trapping ability and plant shape.

The results provided by this study are new quantitative elements for the understanding and evaluation of species ability for sediment retention in degraded lands. They were obtained from hydraulic flume tests to reduce and simplify the influence of the numerous environmental variables in the field and to make the observations comparable and reproducible. These simulations can be discussed for their artificiality and the lack of connection with the field. Nevertheless, despite the simplifications made here, the experimental design proved to be useful for determining the relationships between species ability to trap sediments and their functional traits.

Although the influence of vegetation on sediment deposition and erosion control is well-known (Styzcen and Morgan 1995), few studies have attempted to investigate the way form is related to function. To date, this study is the first to explicitly examine in laboratory conditions the effect on sediment retention of functional traits describing leaf, stem and the whole plant morphology. In future investigations, the experiment could however be improved and extended by using various slopes angles and flow discharges, and a larger selection of species and functional traits. Further experiment should include plant biomechanical properties, such as leaf tensile strength, stem bending resistance or stem lignin and cellulose content, which would better describe stem and leaf toughness. Species set, soil types and the range of experimental parameters tested (i.e. slope angle and flow discharge) should also be expanded.

Current methodologies to determine land vulnerability to erosion are based on local topography and on the percentage of vegetation cover (Rey 2009). Plant functional traits, which appear as relevant parameters to predict species performance for sediment trapping, could be used to add a functional component into such tools and to improve diagnosis. Management of eroded lands could also be improved by considering plant morphological features, such as canopy density and leaf area, when selecting woody species in ecological restoration projects. In addition, plant functions are manifold and plants have indirect effects on ecosystems, often observed in the long term during the restoration process. For example, plants improve the soil hydrological, chemical and physical properties (Cerdà 1998; Bochet et al. 1999). Sediment retention by plants creates mounds which facilitate seedlings establishment and survival of other species (Burylo et al. 2007). Selecting species according to their ability to trap sediment could thus also help enhance vegetation establishment and community diversity.

Conclusion

A functional approach was used to study species ability for sediment trapping at the early stages of plant development. The results showed that canopy density, leaf size and plant shape appear as relevant traits to evaluate and predict species efficiency for sediment trapping. Despite some limitations, this study provided promising results which could have practical implications for ecological restoration of eroded lands and may improve management tools. Plant species provide a variety of ecological functions, such as soil reinforcement or improvement of the soil hydrological, chemical and physical properties, which are as essential as sediment trapping and which must be kept in mind for sustainable restoration of eroded lands.

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