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The effects of vegetation on runoff and soil loss: Multidimensional structure analysis and scale characteristics

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Abstract: This review summarizes the effects of vegetation on runoff and soil loss in three dimensions: vertical vegetation structures (aboveground vegetation cover, surface litter layer and underground roots), plant diversity, vegetation patterns and their scale characteristics. Quantitative relationships between vegetation factors with runoff and soil loss are described. A framework for describing relationships involving vegetation, erosion and scale is proposed. The relative importance of each vegetation dimension for various erosion processes changes across scales. With the development of erosion features (i.e., splash, interrill, rill and gully), the main factor of vertical vegetation structures in controlling runoff and soil loss changes from aboveground biomass to roots. Plant diversity levels are correlated with vertical vegetation structures and play a key role at small scales, while vegetation patterns also maintain a critical function across scales (i.e., patch, slope, catchment and basin/region). Several topics for future study are proposed in this review, such as to determine efficient vegetation architectures for ecological restoration, to consider the dynamics of vegetation patterns, and to identify the interactions involving the three dimensions of vegetation.

Keywords: runoff; soil loss; vertical vegetation structure; plant diversity; vegetation pattern; scale characteristics

1 Introduction

Runoff and soil loss cause substantial on-site and off-site problems such as soil degradation, agricultural productivity decline, flash flooding and the export of nutrients and pesticides, resulting in many ecological and socio-economic problems, especially in arid and semi-arid areas (Pimentel *et al*., 1995; Zuazo and Pleguezuelo, 2008). Runoff and soil loss are affected by several factors, including rainfall characteristics, topographical features, soil properties

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and vegetation (Cammeraat, 2004; Fu *et al*., 2011; Shi and Shao, 2000). The effects of vegetation on runoff and sediment yields are influenced by the structure and function of vegetation (Bautista *et al*., 2007; Bochet *et al*., 1998; Zhu *et al*., 2015). Furthermore, the components of plant species and vegetation pattern are also important factors in controlling soil erosion (Martin *et al*., 2010; Wang *et al*., 2012; Fu *et al*., 2009). Therefore, it is necessary to obtain complete and comprehensive knowledge of the effects of vegetation on runoff and soil loss.

Vegetation can affect runoff and soil loss in various ways (e.g., through vegetation structures, plant diversity levels and pattern distributions). Vertical vegetation structures, including vegetation canopies, litter layers and plant roots, change rainfall redistribution patterns, hydrological processes and soil properties and, in turn, directly or indirectly affect the production of runoff and soil loss (Crockford and Richardson, 2000; Li *et al*., 2014; Quinton *et al*., 1997). Plant diversity, especially functional diversity based on plant traits, is a primary indicator of vegetation composition and community characteristics that controls runoff and soil loss by changing the properties of plants and soils (Janssens *et al*., 1998; Martin *et al*., 2010). The spatial distribution of vegetation forms a spatial mosaic and source-sink landscape pattern that affect surface runoff accumulation and sediment transport (Puigdefabregas, 2005). The selection of vegetation structures and the arrangement of vegetation distributions are critical in controlling runoff and soil loss (Bochet *et al*., 1998; Feng *et al*., 2012; Lu *et al*., 2012). The above vegetation factors play different roles in affecting runoff and soil loss at different spatial scales (Bergkamp, 1998; Mayor *et al*., 2011; Puigdefabregas, 2005). Scale issues in combination with other environmental factors (e.g., climate, topography and soil) complicate the effects of vegetation on runoff and soil loss (Bautista *et al*., 2007; Pannkuk and Robichaud, 2003).

Due to the critical role of vegetation in evaluating runoff and soil loss, the effects of vegetation on runoff and soil loss deserve considerable attention, and abundant information on this issue has been recorded in previous studies. Some reviews on the relationships between vegetation with runoff and soil loss have been published (Gyssels *et al*., 2005; Puigdefabregas, 2005; Smets *et al*., 2008; Zuazo and Pleguezuelo, 2008). Gyssels *et al*. (2005) and Vannoppen *et al*. (2015) proposed that soil loss reduction resulted from the combined effects of plant roots and aboveground vegetation cover and demonstrated the relative importance of these factors for different erosion processes, but they did not consider the role of the litter layer. Smets *et al*. (2008) reported that surface litter effectively conserved soil and water, which were affected by slope lengths and erosion types. Puigdefabregas (2005) reviewed how vegetation patterns affected runoff and soil loss at patch and stand scales, and Gumiere *et al*. (2011) showed that the spatial distribution of vegetated filters was crucial for sedimentological connectivity at the catchment scale, but they ignored the role of vertical vegetation structure. Zuazo and Pleguezuelo (2008) described the effects of vegetation structure and land use patterns on runoff and soil loss, however they did not analyze the effects of plant diversity on runoff and soil loss. Therefore, most previous studies usually explored the role of vegetation based on a particular feature and thus have not adequately explained how vegetation affects runoff and soil loss. Comprehensive analyses on how vegetation controls runoff and soil loss from multidimensional aspects with consideration of scale issues are essential, which is the motivation of the present review.

The objectives of this review are as follows: (1) to systematically summarize the effects of vegetation on runoff and soil loss via a multi-dimensional analysis of vertical vegetation structures, plant diversity and vegetation spatial distribution (Figure 1); (2) to examine the quantitative relationships between vegetation factors and runoff and soil loss; and (3) to evaluate the primary vegetation factors and mechanisms that control runoff and soil loss at different scales. The present work offers insight into the relationships between vegetation runoff and soil loss scales and presents a scientific basis for ecological restoration efforts.

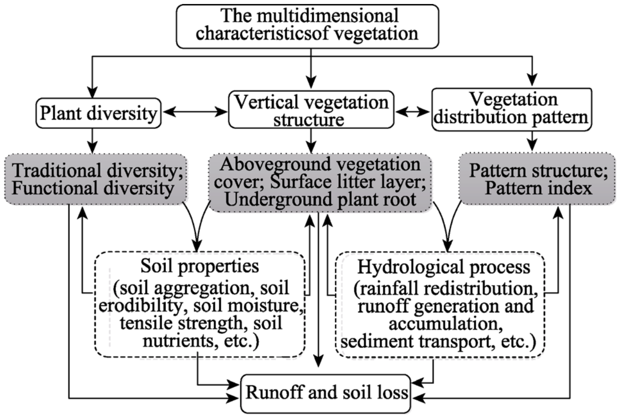

Figure 1 Multidimensional analysis of the effects of vegetation on runoff and soil loss

2 Effects of vertical vegetation structure on runoff and soil loss

2.1 Aboveground vegetation cover

Aboveground vegetation cover is a major factor affecting the production of runoff and soil loss. Vegetation cover redistributes rainfall into three components (i.e., canopy interception, stemflow and throughfall), thereby weakening rainfall, limiting runoff occurrence and controlling soil erosion (Allen *et al.*, 2014; Crockford and Richardson, 2000). Vegetation type and coverage rates are the most important indicators of vegetation cover that affect runoff and soil loss.

2.1.1 Vegetation type

Different vegetation types have different plant morphologies and vegetation structures, leading to differences in rainfall interception and, in turn, affecting the occurrence of splash erosion and runoff accumulation (Bochet *et al.*, 1998; Calder, 2001). In general, under similar environmental conditions (e.g., climate and topography), shrubs are most efficient in reducing runoff and sediment levels, followed by herbaceous plants and trees (Vasquez-Mendez *et al.*, 2010; Wei *et al.*, 2014). However, the effects of vegetation types were influenced by environmental factors, and the effects on preventing runoff and soil loss varied in different regions (Chirino *et al.*, 2006; Nunes *et al.*, 2011; Sánchez *et al.*, 2002; Wei *et al.*, 2007). For example, forests had been found to be more efficient in reducing runoff and soil loss than pastures in Gansu Province of China, with vegetation cover of 59% and 50%, respectively (Wei *et al.*, 2007), but the opposite had been found in Portugal as afforested land with only 15% of vegetation cover with respect to 71% for pasture land (Nunes *et al.*, 2011). In addition, shrub land in Gansu Province of China and Portugal (with 91% and 92% of vegetation cover, respectively) had the least soil loss (Nunes *et al.*, 2011; Wei *et al.*, 2007), but grassland in Spain (with 70% of vegetation cover) showed better effect on reducing soil

Table 1 The relationships of vegetation and soil erosion under different regions

Reference	Region	Climate	Major conclusions
			Vegetation type
Sánchez *et al*. (2002)	Andes, Venezuelan	Tropical humid region	Soil loss rate: horticultural crops > apple tree > pasture > natural forest
Fusun *et al*. (2013)	Sichuan, China	Subtropical humid region	Total runoff and soil loss: grass (mid-coverage) > evergreen tree > shrub > deciduous tree
Nunes *et al*. (2011)	Portugal	Temperate semi-humid region	Runoff rate: afforested land > cereal crop > fallow land > pasture land > shrub land > recovering oak; Soil loss rate: cereal crop > afforested land > fallow land > pasture land > recovering oak > shrub land
Wei *et al*. (2007)	Gansu, China	Temperate semi-arid region	Runoff and soil loss rate: crop land > pasture land > wood land > grassland > shrub land
Chirino *et al*. (2006)	Southeast Spain	Temperate semi-arid region	Runoff and soil loss rate: bare land > shrub land > grassland
			Vegetation coverage
Elwell and Stocking (1976)	Rhodesia	Tropical (semi)humid region	Runoff and soil loss rapidly increased when total vegetal cover fell below 30%, and they kept stability for cover of more than 50%.
Snelder and Bryan (1995)	Baringo, Kenya	Temperate semi-arid region	Soil loss was very low and varied slightly for vegetation cover of 55%–95%, and erosion rates rapidly increased when cover was less than 55%, and reached maximum value for cover of 25% or less.
Moreno-de las Heras *et al*. (2009)	Central-East Spain	Temperate semi-arid region	A sharp transition of sediment yield occurred between 30% and 50% cover. Less than 30% vegetation cover has very different hydrology responses from that of cases with above 50% cover. The restoration of 50% vegetation cover is decisive.
Quinton *et al*. (1997)	Southeast Spain	Temperate semi-arid region	Soil loss decreased significantly when vegetation cover increased from 0 to 30%. When the cover exceeded 70%, there was little change.
Puigdefabregas (2005)		Semi-arid region	Vegetation did not significantly affect runoff and soil loss when the plant cover was less than 10%.
Jiang *et al*. (1992)	Loess Plateau, China	Temperate semi-arid region	Soil loss decreased by more than 90% for cover of 60–70%. Sediment reduction efficiency decreased significantly when cover was less than 40%.

loss than that of shrub land (with 90% of vegetation cover) (Chirino *et al*., 2006). Furthermore, the mean annual precipitation of above regions ranged from 291.7 mm to 823 mm, which was also responsible for the difference of soil loss between different vegetation types. Therefore, the sediment reduction benefit is different under various regions and different types of vegetation.

2.1.2 Vegetation coverage

The coverage rate plays a similarly important role as vegetation type in affecting runoff and soil loss (Elwell and Stocking, 1976). In general, runoff and sediment yields decrease with coverage rates as a linear or exponential function (Figure 2). However, the effects of vegetation on reducing soil loss remain stable when the coverage rate reaches a certain level, i.e., a threshold value, but their effects in terms of reducing runoff continually decrease with an increase in coverage based on the fitted line with average values presented in previous studies, as shown in Figure 2. There are two threshold values of coverage rates: 1) the lower threshold (roughly 10–30%) (Table 1 and Figure 2b), i.e., vegetation can effectively reduce soil loss only when coverage rates reach this threshold value, and 2) the upper threshold (roughly 50–60%) (Table 1 and Figure 2b), i.e., the efficiency of vegetation in reducing soil loss does not increase significantly even when the coverage rate is larger than this threshold value. There are some difference about the threshold values in different regions. As shown in Table 1, Puigdefabregas (2005) concluded that the lower threshold was approximately 10% in semi-arid regions, but it increased to 25% in Kenya (Snelder and Bryan, 1995), to 30% in Spain (Moreno-de las Heras *et al*., 2009; Quinton *et al*., 1997), and even to 40% in the Loess Plateau of China (Jiang *et al*., 1992). For the upper threshold, it was only 50% in Rhodesia (Elwell and Stocking, 1976) and central-east Spain (Moreno-de las Heras *et al*., 2009), while it became 55% in Kenya (Snelder and Bryan, 1995), and it reached 60% or even 70% in the Loess Plateau of China (Jiang *et al*., 1992) and southeast Spain (Quinton *et al*., 1997).

Furthermore, there is a tradeoff between vegetation restoration and water resources in arid and semi-arid areas, and high vegetation coverage rates can result in the depletion of soil water and even land degradation (Wang *et al*., 2011). It is essential to determine appropriate coverage rates for ecological restoration considering the regional differentiation.

2.1.3 Interaction between vegetation type and coverage rate

The effects of vegetation types and coverage rates on runoff and soil loss are related, and their effects should be considered simultaneously to avoid misunderstanding (Bochet *et al*., 1998; Vasquez-Mendez *et al*., 2010). Runoff and soil loss in forests in the Loess Plateau of China (Zhang and Liang, 1996) and shrub in east of Spain (Bochet *et al*., 1998) with higher canopy density levels were much lower than those in sloping farmland and grassland, respectively, but opposite results had been found when forest and shrub land had a lower coverage rate. Furthermore, runoff and soil loss under various vegetation types were significantly different only when the coverage rate exceeded the lower threshold value in semiarid zone of Mexico (Vasquez-Mendez *et al*., 2010). Higher coverage rates of planted patches may weaken differences in soil loss among various vegetation types according to the studies in Kenya (Snelder and Bryan, 1995) and in Spain (Quinton *et al*., 1997).

2.2 Surface litter layer

The litter layer is characterized by its key eco-hydrological functions (i.e., intercepting rainfall, increasing infiltration, interfering with evaporation, decelerating surface runoff, and preventing soil loss) (Li *et al*., 2014; Pannkuk and Robichaud, 2003; Wang *et al*., 2013). Furthermore, litter layers can improve soil properties and can help soil resist erosion. Litter types, biomass, coverage rates and thicknesses are the main indicators that affect the degrees to which litter layers conserve soil and water (Findeling *et al*., 2003; Li *et al*., 2013; Smets *et al*., 2008).

Litter layers of different vegetation types present significantly different capacities to intercept rainfall and reduce soil loss (Pannkuk and Robichaud, 2003; Singer and Blackard, 1978). Generally, litter layers have a stronger effect on sediment transport processes than soil detachment, and the effects of litter layers on erosion processes (e.g., interrill and rill erosion) vary among layer types (Pannkuk and Robichaud, 2003). For example, broadleaf and needle forest litter in Northern China reduced runoff yields by 29.5% and 31.3%, respectively, and sediment yields by 85.1% and 79.9%, respectively (Li *et al*., 2014).

Litter biomass has a considerable effect on runoff and soil loss, although its effects are

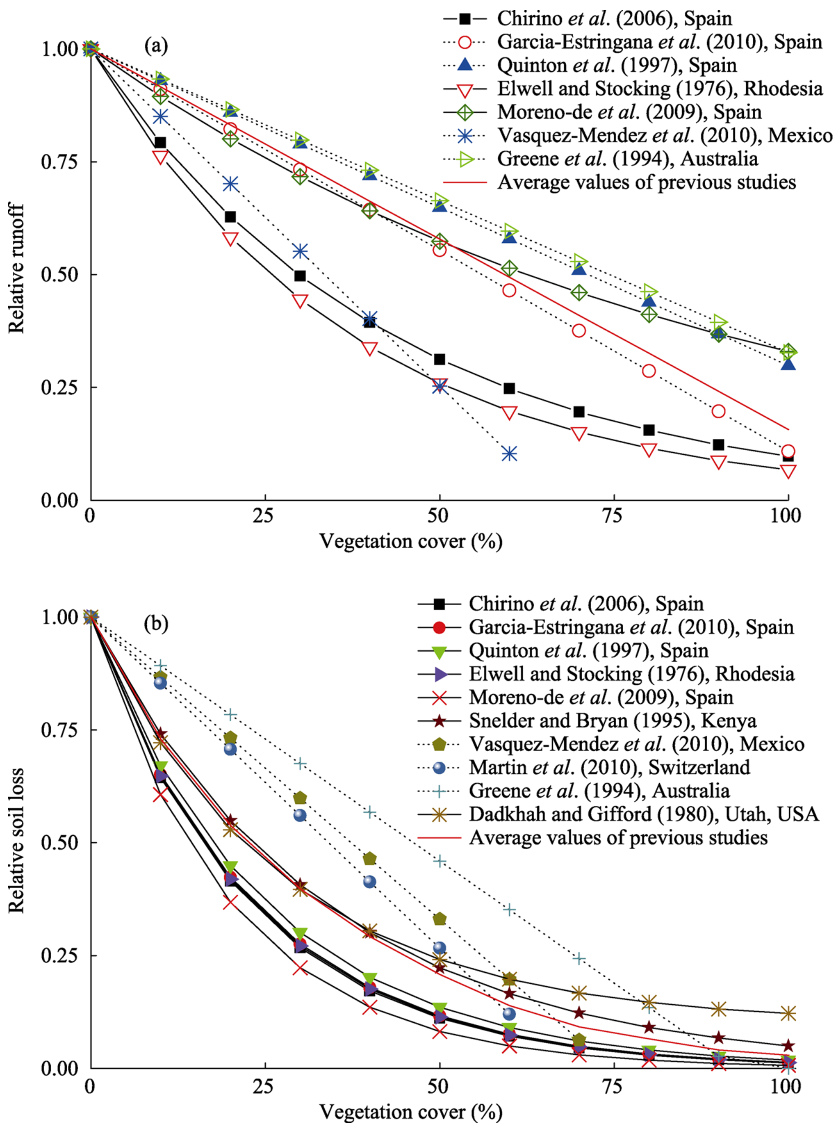

Figure 2 Relationships between vegetation cover and (a) relative runoff (compared to runoff on bare soil) and (b) relative soil loss (compared to soil loss on bare soil)

Note: The dotted and solid lines with marks denote linear and exponential relationships, respectively. The red solid line denotes the fitted results with average values from previous studies. Study areas are shown in the legend followed references

subject to litter types. The runoff coefficient and soil loss rate generally decrease with litter biomass levels (Findeling *et al*., 2003). In addition, litter biomass has a threshold value as vegetation coverage rates. Runoff and soil loss remain stable when litter biomass levels reach a threshold value, as a flow channel for runoff is formed by excess litter cover, thus preventing water infiltration (Findeling *et al*., 2003; Li *et al*., 2014).

The litter coverage rate is negatively related to runoff and soil loss, and an exponential relationship has been observed between these parameters (Bochet *et al*., 1998; Shi *et al*., 2013). Higher litter coverage levels abate sediment transport, especially for clay- and silt-sized particles (Shi *et al*., 2013). Furthermore, the spatial distribution of litter cover under the same coverage rate significantly affects soil erosion (Singer and Blackard, 1978). Litter thickness is positively correlated with a delay in runoff generation (Liu *et al*., 1991). It has also been reported that when litter layers reach a certain thickness (2 cm), they can minimize or fully prevent the occurrence of soil erosion in the Loess Plateau of China (Wu *et al*., 1998).

2.3 Underground roots

2.3.1 Effects of plant roots

Compared to aboveground vegetation cover and surface litter layers, considerable attention has not been paid to the role of underground roots in affecting runoff and soil loss (Gyssels *et al*., 2005; Katuwal *et al*., 2013; Sánchez *et al*., 2002). Gyssels *et al*. (2005) reviewed that the aboveground vegetative cover was the most important factor to splash and interrill erosion processes, while roots were as important as aboveground vegetation cover for rill and gully erosion processes. Furthermore, the relative contribution of roots to runoff and soil loss reduction varied with vegetation types. The contribution of roots to reduce runoff and soil loss was relatively greater than that of shoots under forest land, while the effects of shoots and roots on soil loss were nearly equal under grassland in the Loess Plateau of China (Zhang *et al*., 2014).

Roots conserve soil and water through two means: 1) roots can directly protect soil detachment and increase infiltration, thus reducing runoff and soil loss (De Baets and Poesen, 2010; Gyssels *et al*., 2006; Reubens *et al*., 2007), and 2) roots can improve soil properties by increasing soil organic matter levels, enhancing the quantity of soil stable aggregates and stabilizing soil layer structures, and subsequently reduce the soil detachment rate (Mamo and Bubenzer, 2001; Pohl *et al*., 2009).

Many studies have researched the approaches that roots enhance soil anti-erodibility and reduce soil detachment (De Baets *et al*., 2011; Reubens *et al*., 2007; Zhou and Shangguan, 2005). Roots reinforce soil in two directions: horizontal and vertical (Burylo *et al*., 2012b; De Baets *et al*., 2008; Genet *et al*., 2005; Reubens *et al*., 2007). The downward penetration of roots strengthens soil anti-shear capacities, whereas laterally extensive roots reinforce soil stability through their tensile strength (De Baets *et al*., 2008; Reubens *et al*., 2007). Roots form underground networks in the above two directions to bind soil particles and then increase soil cohesion.

2.3.2 The relationships of root indexes with runoff and soil loss

The mechanical properties, distribution depths and densities of effective roots (diameter < 1 mm) are the main indicators that affect runoff and soil loss. Effective roots with great tensile strength improve soil properties and limit soil loss (Genet *et al*., 2005; Pohl *et al*., 2009). Roots positioned at a depth of 0–30 cm in shrubland and grassland and at 0–60 cm in forests critically affected soil loss in Loess Plateau of China (Liu and Li, 2003). In quantifications of the effects of roots on runoff and soil loss, the distribution density of root systems often acts as a major indicator, including root density (RD), root length density (RLD) and root surface area density (RSAD) (Burylo *et al*., 2012b; Pohl *et al*., 2009; Reubens *et al*., 2007). In general, the infiltration capacity of soil water increases with increased RD levels, and in turn, the potential for runoff generation is reduced (Himmelbauer *et al*., 2013). RD and RLD are positively correlated with soil stable aggregate levels (Pohl *et al*., 2009), and their effects on soil detachment are shown in Figure 3. Relationships between soil detachment rates

(SDRs) and RD or RLD are exponential for interrill and rill erosion, whereas RD and RLD have almost no effect on SDR for splash erosion. Throughout soil erosion development (i.e., from splash to interrill and rill), the efficiency of RD and RLD in reducing soil loss increases. Furthermore, the RSAD is linearly correlated with soil loss and infiltration rates according to rainfall simulation experiments conducted in Shaanxi Province, China (Zhou and Shangguan, 2007).

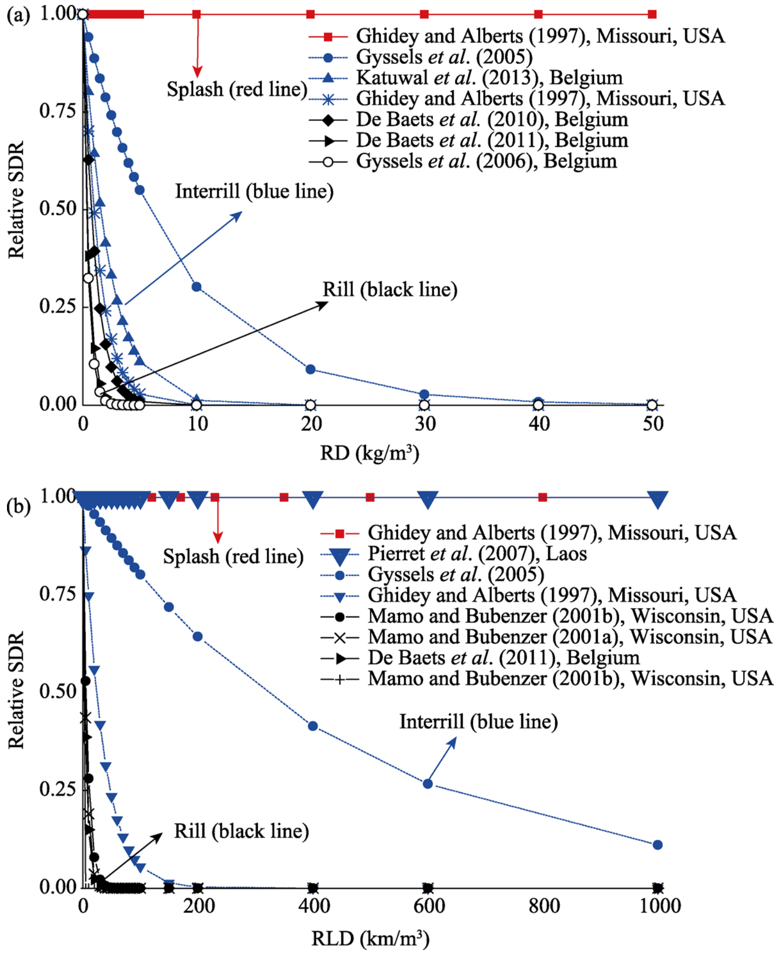

Figure 3 Relationships between the relative soil detachment rate (SDR, relative to detachment for bare soil) and (a) root density (RD) and (b) root length density (RLD) for splash (red line), interrill (blue line) and rill (black line) erosion processes.

Note: data of Gyssels *et al*. (2005) was concluded from different regions

3 Effects of plant diversity on runoff and soil loss

Vertical vegetation structure plays a key role on runoff and soil loss at the individual plant scale. However, at the community and ecosystem scales, plant diversity is significantly related to runoff and soil loss (Martin *et al*., 2010; Pohl *et al*., 2009; Zhu *et al*., 2015). Plant diversity can affect runoff and soil loss by changing the pattern of vertical vegetation structure. Increased plant diversity levels strengthen the efficiency of aboveground vegetation cover and increase the diversity of litter layers and roots to control runoff and soil loss

(Martin *et al.*, 2010; Pohl *et al.*, 2009; Zhou and Shangguan, 2005). Furthermore, plant diversity changes soil physical and chemical properties and indirectly affects runoff and soil loss (Bezemer *et al.*, 2006; Janssens *et al.*, 1998; Pohl *et al.*, 2009). There are two types of plant diversity indicators: the traditional diversity index based on species components and the functional diversity index based on plant traits.

3.1 Effects of traditional plant diversity

Under similar vegetation cover rates, components of more plant species tend to cause an evident decrease in runoff and soil loss (Martin *et al.*, 2010). A negative linear correlation was found between runoff frequency and the plant richness index, and the total amount of runoff and sediment are negatively exponentially correlated with the plant richness index (Wang *et al.*, 2012) and Shannon Index (Bautista *et al.*, 2007). In contrast, studies have shown that there is no significant correlation between plant diversity and soil loss and that it is difficult to identify how plant diversity controls runoff and soil loss, as plant diversity interacts with other plant factors (Shrestha *et al.*, 2010; Casermeiro *et al.*, 2004).

3.2 Effects of plant functional diversity

Compared to traditional plant diversity, functional diversity (FD) is based on plant morphology and physiology in investigating the relationship between community structures and ecological processes (Burylo *et al.*, 2012a; Martin *et al.*, 2010; Villeger *et al.*, 2008). As ecological processes are largely determined by the functional identities of dominant species, the FD can explain more variations in ecological processes than species richness (Mokany *et al.*, 2008; Villeger *et al.*, 2008). Vegetation types, leaf area indexes, biomass levels, root distributions and tensile strengths are considered in the FD, and thus, the FD is highly correlated with soil erosion rates (De Baets *et al.*, 2008; Mouillot *et al.*, 2011; Villeger *et al.*, 2008). Villeger *et al.* (2008) proposed the following three FD indexes to describe community functional compositions: functional richness (FRic), functional evenness (FEve) and functional divergence (FDiv). The FDiv has a robust negative effect on soil erosion (Zhu *et al.*, 2015). Combining functional diversity with erosion processes proved to be an essential and new approach to explore the effects of plant diversity on runoff and soil loss.

3.3 Effects of plant diversity on soil properties

Plant diversity and soil properties interact with one another, forming mechanisms of plant-soil feedback that are widely found in ecosystems (Bezemer *et al.*, 2006). In general, increased plant diversity levels improve soil properties and enhance their capacities to conserve soil and water (Hooper and Vitousek, 1998). Several studies have found that plant diversity can significantly contribute to nitrogen cycling and can change microbial community compositions (Carney and Matson, 2006; Hooper and Vitousek, 1998; Steinauer *et al.*, 2015), and thus increase soil carbon storage levels and soil N, P and K content (Hager, 2012; Hooper and Vitousek, 1998; Janssens *et al.*, 1998). Moreover, plant diversity has a positive effect on soil stable aggregates and soil porosity, thus enhancing water permeability and the stability of soil in reducing runoff and soil loss (Martin *et al.*, 2010; Pohl *et al.*, 2009; Wang *et al.*, 2012).

4 Effects of vegetation spatial distribution on runoff and soil loss

Spatial distribution of vegetation heavily affects ecological processes in arid and semi-arid regions (Puigdefabregas, 2005; Zhang *et al*., 2014a). Several studies have classified land cover types into vegetation and bare patches as a basis for researching the effects of vegetation spatial distribution (Imeson and Prinsen, 2004; Liu *et al*., 2013; Puigdefabregas, 2005; Zhang *et al*., 2014b). Vegetation patches act as "sinks" that trap runoff and sediment, while bare patches act as "sources" (Cerda, 1997; Puigdefabregas, 2005). Vegetation and bare patches form spatial mosaics (i.e., source-sink landscape patterns) that change landscape connectivity levels and thereby shape the collection of surface runoff and sediment delivery (Bautista *et al*., 2007; Mayor *et al*., 2008; Puigdefabregas, 2005). The source-sink structure and landscape connectivity act as dominant landscape characteristics that control runoff and soil loss (Cerda, 1997; Liu *et al*., 2013; Ludwig *et al*., 1999).

4.1 Effects of land cover patterns on runoff and soil loss

Land cover patterns, i.e., the spatial distribution of vegetation and bare patches, can greatly affect runoff and sediment yields (Bartley *et al*., 2006; Bautista *et al*., 2007). The capacities of stripes and strand banded patterns in converting rainfall into soil water were approximately 8% higher than those of stippled patterns in the semi-arid woodlands of Eastern Australia (Ludwig *et al*., 1999). However, stripes parallel to a slope direction caused more runoff and sediment loss than stippled patches in the Loess Plateau of China (Zhang *et al*., 2014a; Zhang *et al*., 2014b). The configuration of different vegetation types along the slope extension is as important as mosaic vegetation patterns (Bautista *et al*., 2007; Fu *et al*., 2009). According to Fu *et al*. (2009), land use combinations of 'grass + mature forest + grass' and 'grass + young forest + mature forest + grass' on hill slopes in the Loess Plateau of China can better control soil erosion than 'grass + shrub' patterns.

Patch locations constitute another feature of land cover patterns that controls runoff and soil loss (Bartley *et al*., 2006; Ludwig *et al*., 2002; Ludwig *et al*., 1999). More runoff and sediment yields are generated when bare patches are closer to water outlets, whereas the presence of vegetation patches near an outlet can effectively trap runoff and sediment (Bartley *et al*., 2006). It should be noted that vegetation at the bottom of a slope significantly reduces runoff and sediment yields only when the coverage rate exceeds a certain value (e.g., 20%) (Rey, 2004). In addition, stripe patterns near water outlets are more efficient at reducing runoff and sediment levels than are scattered patches (Bautista *et al*., 2007; Ludwig *et al*., 1999).

4.2 Application of pattern indexes to represent vegetation spatial distribution

To quantify the effects of land cover patterns on runoff and soil loss, several pattern indexes have been developed to describe the characteristics of vegetation spatial distribution (Bautista *et al*., 2007; Imeson and Prinsen, 2004; Jaeger, 2000; Ludwig *et al*., 2007). The landscape indexes can be divided into two categories: landscape fragmentation and connectivity indexes (Table 2). Landscape fragmentation and connectivity indexes often have opposite effects on runoff and soil loss. In general, the landscape fragmentation indexes shown in Table 2 (e.g., PD, ED, AI and D) present a negative relationship with runoff and soil loss.

A framework is proposed in Figure 4 to denote the relative influence of landscape fragmentation and connectivity on runoff and soil loss. Landscapes that tend to be more connective increase runoff and sediment production potential.

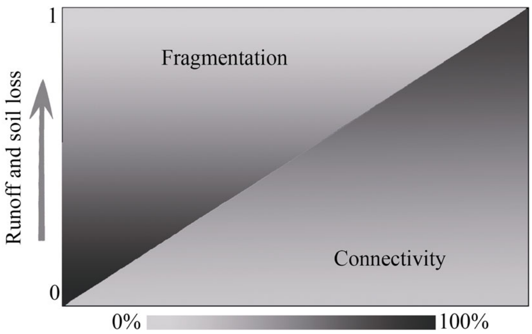

Figure 4 The relative potential for runoff and soil loss reduction with changes in landscape fragmentation and connectivity
Source: based on the relationships shown in Table 2.

Most pattern indexes, such as those included in FRAGSTATS, were not developed based on detailed ecological processes and are therefore difficult to use to explicitly measure runoff and soil erosion (Imeson and Prinsen, 2004; Liu *et al*., 2013; Ludwig *et al*., 2002). Furthermore, there are uncertainties and contradictions in the relationships between pattern indexes and runoff and soil erosion (Liu *et al*., 2013; Ludwig *et al*., 2002; Ouyang *et al*., 2010). As pattern indexes are interdependent, it is difficult to show how landscape patterns prevent soil erosion using a single pattern index (Bautista *et al*., 2007; Hou *et al*., 2014).

Recently, pattern indexes with physical meaning were developed to measure runoff and soil erosion. Ludwig *et al*. (2002) developed the Directional Leakiness Index (DLI) to determine the potential for a given hillslope vegetation pattern to maintain materials (e.g., soil particles and water), and it was found to be positively and linearly correlated with runoff and exponentially correlated with sediment yields in southeast Spain (Bautista *et al*., 2007). Mayor *et al*. (2008) created the Flowlength index, which delineated the pathway length of water flows from each location to sinks such as vegetation patches and topographical depressions (ponds). The index revealed a significantly linear relationship with runoff and sediment yields in southeast Spain. Liu *et al*. (2013) modified the above two indexes by considering the functional heterogeneity of plant cover types and landscape positions. Fu *et al*. (2006) and Zhao *et al*. (2012) proposed a multi-scale soil loss evaluation index that reflects the effects of land use patterns on soil erosion based on the RUSLE C-factor and scale-pattern-process theories. Although the above indexes are significantly correlated with runoff volumes and soil loss and can describe the effects of vegetation spatial distribution, they cannot easily predict runoff and soil erosion levels. It is essential to develop indexes based on detailed hydrological processes in consideration of threshold behaviors and feedback mechanisms to quantify runoff and soil erosion.

5 Scale issues on the relationships of vegetation factors with runoff and soil loss

Scale issues are challenges in the study of runoff and soil loss. Levels and mechanisms of runoff and soil loss and influencing factors are scale-dependent (Ferreira *et al*., 2005; Nadal-Romero *et al*., 2011). Runoff and soil loss also present different characteristics and restrictions at different scales (Cammeraat, 2004; de Vente and Poesen, 2005). Furthermore, the sources of runoff and sediment often change across scales. Runoff at small scales mainly results from overland flow (Bautista *et al*., 2007; Chaplot and Poesen, 2012; Liu *et al*., 2013), whereas at large scales, base flows reaching stream channels through infiltration

Table 2 Definition of pattern indexes and their relationships with runoff and soil loss

Pattern index	Abbreviation	Definition	Relationship with runoff and soil loss	Country	Reference
Total Landscape Area	TA	The total vegetation patch area of a landscape.	Negative exponential	China	Hou *et al*. (2014)
Patch Density	PD	The number of patches per unit area.	Negative second order polynomial	Spain; China	Bautista *et al*. (2007); Ouyang *et al*. (2010)
Edge Density	ED	The total length of all edge segments per unit area for the class or landscape under consideration.	Negative second order polynomial	China	Ouyang *et al*. (2010)
Shannon's Diversity Index	SHDI	A measure of patch diversity for a landscape.	Negative; Mixed linear (from positive to negative)	Spain; China	Bautista *et al*. (2007); Hou *et al*. (2014)
Aggregation Index	AI	A measure of the aggregation of spatial patterns that is scaled to account for the maximum possible number of similar areas in any given landscape composition.	Negative linear	China; USA	Hou *et al*. (2014); He *et al*. (2000)
Lacunarity	Lacunarity	A scale-dependent measure of heterogeneity describing the shape and distribution of gap sizes in fractal geometric landscapes.	_	Spain; *	Imeson and Prinsen (2004); Plotnick *et al*. (1993)
Bare Area Fragmentation Index/Degree of Landscape Division	D	The probability that two randomly selected places on the map examined are not situated in the same undissected area, determining how strongly vegetation patches dissect the bare area.	Negative	Spain; Germany	Imeson and Prinsen (2004); Jaeger (2000)
Directional Leakiness Index	DLI	A measure of the distances between patches, indicating the connectivity of bare patches and the potential for a given vegetation pattern to retain resources flowing across surfaces.	Positive linear (runoff); Positive exponential (soil loss)	Australia; Spain	Ludwig *et al*. (2002); Bautista *et al*. (2007)
Modified Directional Leakiness Index	DLI_M	A modified DLI that is corrected by incorporating the effect of cover types on runoff and sediment generation compared to bare soil and the flow path length to the outlet of each location.	Positive linear	China	Liu *et al*. (2013);
Flowlength Index	Flowlength	A measure of the average length of all potential runoff pathways in a landscape based on the connectivity of bare patches (source areas) related to vegetation cover and topography.	Positive linear	Spain	Mayor *et al*. (2008)
Modified Flowlength Index	Flowlength_M	The modified Flowlength index based on the effect of cover types on runoff and sediment generation compared to bare soil and the flow path length to the outlet of each location.	Positive linear	China	Liu *et al*. (2013)
Index of Connectivity	IC	A potential connectivity characteristic between sediment eroded from hillslopes and the stream system based on GIS data.	Positive	Italy	Borselli *et al*. (2008)

(*To be continued on the next page*)

(*Continued*)

Pattern index	Abbreviation	Definition	Relationship with runoff and soil loss	Country	Reference
Field Connectivity Index	FIC	An assessment index similar to the IC that is based on field approaches using signs of water flow and sedimentation and that represents ground truth subdivided into upslope and downslope components.	Positive	Italy	Borselli *et al*. (2008)
Upslope Side Length of Vegetation Patch	U	An index denoting vegetation patch capacities to catch water flowing downslope.	Negative	Spain	Imeson and Prinsen (2004)
Connectivity of Bare Patches	C	An index of the potential runoff length describing the degree of connectivity between bare (source) areas within a vegetation-bare soil mosaic landscape (map).	Negative	Spain	Imeson and Prinsen (2004)
Location-weighted Landscape Contrast Index	LCI	An index for assessing the effect of landscape patterns on sediment yields based on the contributions of different land cover types (source and sink) to soil erosion in a watershed.	Positive	China; China	Chen *et al*. (2003); Yang *et al*. (2012)
Soil loss Evaluation Index	SL	An index for evaluating the relationship between land use patterns and soil erosion based on the main factors of soil erosion, which can be applied at different scales. By upscaling (from a slope to a watershed), more topography factors are considered.	_	China	Zhao *et al*. (2012)

'_' denotes that a relationship is not clear, and '*' means that there is no definite country.

should be considered as an important source (Cammeraat, 2004; Ferreira *et al*., 2005). At patch and slope scales, sediment mainly results from splash, interrill and rill erosion (Bochet *et al*., 2006; Gyssels and Poesen, 2003; Wang *et al*., 2013; Zhou and Shangguan, 2005). However, at watershed and larger scales, in addition to rill erosion, gully erosion and river-bank collapse constitute major sources (de Vente and Poesen, 2005; Pannkuk and Robichaud, 2003; Shi and Shao, 2000). As a result, it is difficult to achieve a direct scaling of runoff and soil loss. Patterns of runoff and soil loss and effects of vegetation should be summarized at different scales from a hierarchical perspective (Bergkamp, 1998).

Figure 5 presents major vegetation factors of runoff and soil loss at different scales. The functions of vegetation in conserving water and soil are also scale dependent. Furthermore, the effects of vegetation on runoff and soil loss at different scales are subject to other environmental factors (e.g., climate, topography, and soil properties). Specially, extreme rainfall events may increase the complexity and uncertainty of the effects of vegetation on erosion processes (González-Hidalgo *et al*., 2007; Wei *et al*., 2009). Heavy rain storms often caused landslides, debris flows, flooding and severe soil erosion, which had 1.5–53.1 times of erosion rate than mean annual rates and accounted for more than 50% or even 75% of annual soil erosion (Cheng *et al*., 2002; González-Hidalgo *et al*., 2007; Ramos and Marti-

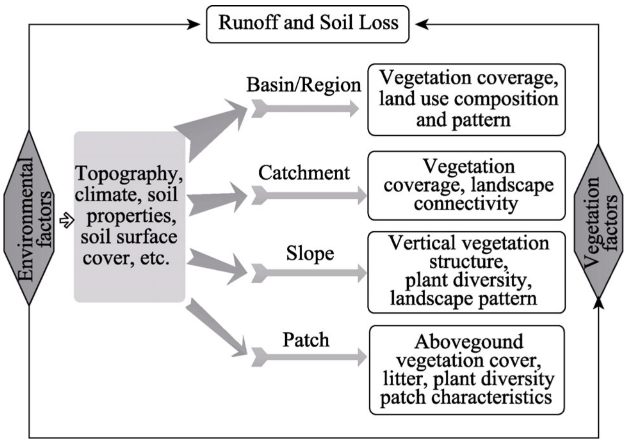

Figure 5 Major vegetation factors of runoff and soil loss at different scales and the effects of environmental factors
Note: The width of the arrow denotes the level of the influence of environmental factors.

nez-Casasnovas, 2009; Shi and Shao, 2000; Wei *et al*., 2009). However, extreme rainfall events not always led to serious erosion, which depended on other factors such as crop growth stage, vegetation cover and cultivated landscapes (Boardman, 2015). Generally, the impacts of environmental factors increase with scale expansion (Figure 5).

At the patch scale, vertical vegetation structure (plant morphology, vegetation coverage rates and surface litter layers) is the main vegetation factors that control runoff and sediment yields (Bochet *et al*., 1998; Dadkhah and Gifford, 1980; Martin *et al*., 2010; Snelder and Bryan, 1995). Within the same area of vegetation cover, plant diversity acts on runoff and soil loss (Martin *et al*., 2010). Influenced by patch characteristics, soil properties, surface rocks and surface crusting affect erosion processes (Bautista *et al*., 2007; Cammeraat, 2004; Pannkuk and Robichaud, 2003).

At the slope scale, due to the development of interrill and rill erosion, in addition to aboveground vegetation cover and litter, plant roots must be considered as a crucial factor (Gyssels *et al*., 2005). Vegetation distribution patterns determine landscape fragmentation and connectivity, and plant diversity contributes greatly to runoff and sediment yields (Bautista *et al*., 2007; Hou *et al*., 2014; Pohl *et al*., 2009; Wei *et al*., 2014). Several studies have concluded that topography (e.g., slope gradient and slope length) shapes the effects of vegetation on runoff and sediment (Donjadee and Chinnarasri, 2012; Liu *et al*., 2012; Sadeghi *et al*., 2013). In addition, landscape connectivity affects runoff to a greater extent in heavy rainfall-runoff events (Bautista *et al*., 2007; Mayor *et al*., 2008).

At the catchment scale, although vegetation coverage still contributes significantly to runoff and sediment yields, such effects weaken with an increase in watershed area and variation in land use types (Cammeraat, 2004; de Vente and Poesen, 2005; Pierret *et al*., 2007). In such cases, landscape connectivity plays a key role in the production of runoff and sediment loads that enter river channels, and topographic features and the connectivity of channel networks become major factors that control the transport of runoff and sediment yields into catchment outlets (Cammeraat, 2004; Ferreira *et al*., 2005; Mayor *et al*., 2011).

At the basin and regional scales, land use compositions and patterns are the main vegetative factors that explain variations in sediment yields (Fu *et al*., 2011; Lu *et al*., 2012; Shi *et al*., 2014). Sediment sinks have a more central role than sources, and vegetation restoration is very effective in decreasing runoff and sediment yields (Butt *et al*., 2010; de Vente and Poesen, 2005; Feng *et al*., 2012; Lu *et al*., 2012). The relationship between runoff and sediment in a basin channel is determined based on regional landforms, i.e., the topography of hills and slopes, river network characteristics and connections between channels

(Cammeraat, 2004). Variations in regional precipitation also create differences in vegetation cover and erosion levels among different regions (Feng *et al*., 2012; Lu *et al*., 2012).

6 Further issues and prospects

This paper summarizes the effects of vegetation on runoff and soil loss in various dimensions (e.g., vertical vegetation structures, plant diversity and vegetation spatial distribution) and their scale characteristics. The relationships involving vegetation, erosion and scale are summarized in Figure 6, which shows the relative importance of each dimensional characteristic in various erosion processes across scales. With erosion development (from splash to gully), the main factor of the vertical vegetation structure in controlling runoff and soil loss changes from aboveground vegetation cover to roots. Furthermore, plant diversity exhibits a closer relationship with vertical vegetation structure and plays a more critical role at smaller scales, while landscape patterns closely related to canopy cover also play a critical role across scales. Therefore, considering a certain dimension of vegetation characteristics alone cannot fully explain how vegetation affects runoff and soil loss. The findings presented here serve as a key reference for vegetation restoration efforts to control runoff and soil loss at different scales.

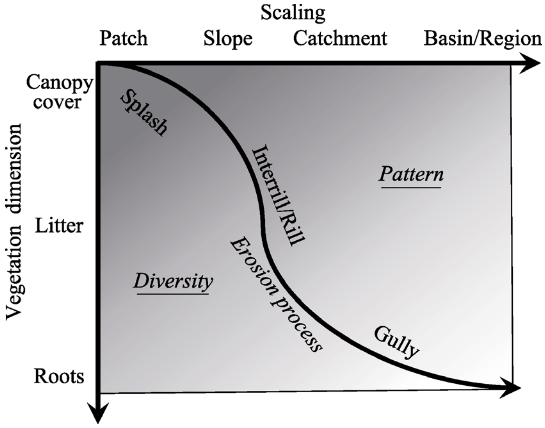

Figure 6 Framework of the relationships among vegetation, erosion and scale
Note: the darker color denotes a stronger relationships between vegetation factors and a given erosion process.

Certain issues are in need of further study. (1) First, it is necessary to identify isolated ways in which different vertical vegetation components control runoff and soil loss. The three aspects of vertical vegetation structure have their own functions, and their efficiencies are interdependent. Understanding their roles will be useful for determining the efficient architectures and morphologies of vegetation for ecological restoration. (2) Second, more effort should be made in quantifying the vertical structure of vegetation and incorporating it to the models such as RUSLE to meet the forecast demand. (3) Third, we should develop a comprehensive approach to describe the dynamics of vegetation patterns and incorporate them into pattern index based on detailed hydrological processes, which can be used to quantitatively predict runoff and soil loss levels. (4) Fourth, the relative importance of each dimension and the interactions among the three dimensions of vegetation in affecting runoff and soil loss at different scales should be determined. (5) Finally, we must enhance efforts to describe the quantitative relationships between vegetation factors and runoff and soil loss at different scales and develop upscaling models that relate the results at different scales.

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