

Linking fine root and understory vegetation to channel erosion in forested hillslopes of southwestern China

Y. Li · H. Q. Yu · N. Zhou · G. Tian · J. Poesen ·
Z. D. Zhang

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Abstract

Aims The forestland understory vegetation reduces concentrated overland flow through infiltration improvement by roots and raindrop interception by surface cover. However, little has been done to quantify the linkages between understory vegetation cover, roots, and channel erosion, and such information can help assessing the role of the reforestation in soil erosion control. In this study, we evaluated the relationships between channel density, root density,

and vegetation cover in forested hillslopes of southwestern China.

Methods Twelve locations (four slopes and three positions) of forested hillslopes with a wide range of understory degradation due to litterfall extraction and livestock grazing were selected for the study. Channel density as a measure of rill and (small) gully erosion, root density of different diameter classes, and vegetation cover of all types were determined using field measuring, soil coring and the line transect method, respectively. Soil loss rates were estimated using the caesium-137 (^{137}Cs) technique.

Results Rills (depth < 0.3 m) with a width of 0.05–0.1 m were the dominate channel erosion in all hillslopes with understory-degradation, and small gullies (depth > 0.3 m) with a width 0.5–1.0 m were found at the locations of hillslopes with high understory-degradation. Channel density and soil loss rate increased with the increase in understory-degradation in the forested hillslopes. Simple correlation analysis indicated that channel density was negatively correlated with fine root density (diameter < 1 mm and 1–2 mm) and grass and shrub covers, but not with coarse roots (diam. 2–5 mm and 5–10 mm) and mulch and tree covers. The principal component regression revealed fine root density (diam. < 1 mm), shrub and grass covers were the most important predictors for channel density in the forested hillslopes. Tree cover, mulch cover and coarse root density were found to have much less influence on channel density. For the model established from this study using principle component regression, vegetation variables could explain 82 % variance of channel density.

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Y. Li (✉) · H. Q. Yu · N. Zhou · Z. D. Zhang
Agricultural Clean Watershed Research Group, Institute of
Environment and Sustainable Development in Agriculture,
Chinese Academy of Agricultural Sciences (CAAS),
Beijing 100081, China
e-mail: liyong@caas.cn

G. Tian
Environmental Monitoring and Research Division,
Monitoring and Research Department, Metropolitan Water
Reclamation District of Greater Chicago,
Lue-Hing R&D Complex, 6001 W. Pershing Road, Cicero, IL
60804, USA

G. Tian
Department of Civil, Architectural and Environmental
Engineering, Illinois Institute of Technology,
3201 South Dearborn Street, Chicago, IL 60616, USA

J. Poesen
Physical and Regional Geography Research Unit, Catholic
University Leuven,
Redingenstraat 16, 3000 Leuven, Belgium

Conclusions We conclude that fine root density and grass and shrub covers are the most important factors in controlling soil erosions in forested hillslopes. These parameters should be taken into consideration in assessing reforestation for soil erosion control in hilly areas such as that in southwestern China or other similar regions.

Keywords Channel density · Fine root · Rill and gully erosion · Grass and shrub cover · Forest hillslope · China

Introduction

Channel (rill and gully) erosion by concentrated overland flow is a global concern as it leads to increased sediment production and land degradation (Poesen et al. 1998; Li et al. 2004; Valentin et al. 2005). Through source tracking, researchers in Australia and China have found that the majority of sediments in watersheds are produced by gully erosion (Li et al. 2003; Hughes et al. 2009). Understanding the factors that cause channel initiation in a landscape can lead to development of improved management practices that can increase productivity and ecosystem services of the land (Poesen et al. 1998).

Channel initiation could be related to a wide range of factors, including rainfall intensity, flow hydraulics, topography, soil texture, surface features, vegetation and land use (Valentin et al. 2005; Kirkby and Bracken 2009). Vandekerckhove et al. (2000) found that gully initiation in Mediterranean areas was more dependent on vegetation type and the extent of cover than rainfall amount. In semiarid central Mexico, Rebeca et al. (2010) reported that runoff and soil erosion were reduced by vegetation patches. Moreno-de las Heras et al. (2009) found that a 50 % vegetation cover was the threshold for channel initiation in reclaimed mining soils in Spain. Surface vegetation reduces water-induced soil erosion by intercepting runoff, increasing water infiltration, and retarding flow velocities (Styczen and Morgan 1995). Sorriso-Valvo et al. (1995) found that ground plant cover more effective than canopy cover in controlling runoff and erosion. In a forest, interception of rain by tall trees may form larger and higher kinetic energy drops, and thus, the tree coverage might even favor soil crusting, runoff generation and gully initiation (Hall and Calder 1993). The myriad roles that vegetation cover plays in protecting soils from erosion indicate that vegetation functions in a highly

complex manner that is best addressed by considering the interaction of multiple variables.

Roots also play a critical role with respect to soil erosion control (Li 1995; Ghidry and Alberts 1997; De Baets et al. 2007). Plant roots enlase and concrete soil, and this can stabilize soil structure and limit soil movement (Tengbeh 1993). A study by Archibold et al. (2003) found that gully retreat was delayed by tree root mats that bound surface soil. Plant roots can also indirectly improve soil hydrological characteristics, therefore, reducing concentrated flow erosion. Gyssels and Poesen (2003) showed that an increase in shoot and root density resulted in an exponential decrease of concentrated flow erosion rates. Gray (1978) noted there was a non-linear inverse relationship between root diameter and strength, thus smaller roots could contribute more strength per unit root area in relation to control of channel initiation. Li et al. (1991) defined effective roots (i.e. those that inhibit erosion) as having fibrils less than 1 mm in diameter, and densely distributed at depths of 0–30 cm. Poesen et al. (2006) pointed out below ground biomass mechanisms should be considered in models predicting soil erosion. Yet, little is known about the effects of fine roots along with shrub and grass cover on channel erosion in forest hillslopes (Valentin et al. 2005; Poesen et al. 2006).

China manages the world's largest forest plantations (Piao et al. 2009) with the objectives of controlling soil erosion through the establishment of tree canopies. However, many forested hillslopes in southwestern China are still experiencing rill and gully erosion (Zhao 2006). For instance, in the Changshanling mountain area (800 ha) in southwestern China gullies occupy 13 % of the forested land area. Human activity mainly (litterfall extraction and livestock grazing) have severely impacted the forested hillslopes of southwestern China. Grazing in the forest was known to reduce the density and biomass of grass grown under trees, and livestock could compact soil and retard root development (Belsky and Blumenthal 1997), thus causing degradation of understory in the forest. The degradation of understory as the loss of grass and shrub cover and possibly the fine root biomass could have contributed to the channel erosion in the hillslope forest of southwestern China. However, little is known about understory cover, root biomass and their relationship with channel erosion in the large forested region, and so far, this issue has not been considered in assessing the role of Chinese reforestation. Our investigation of the Xinying catchment, located in the Changshanling mountain area of southwestern China, began with the hypothesis that the

extent of forested hillslope erosion depends on fine root and contact cover of shrub and grass, given the same climate, topsoil and topographic conditions.

The objectives of the present study were to (1) investigate spatial variations in channel density, root density and vegetation cover across forested hillslopes with a wide range of understory degradation; (2) evaluate the importance of fine root density and grass and shrub cover variables relative to other vegetation factors in relation to channel erosion; and (3) establish relationships between root density, vegetation cover and channel density in forested hillslopes.

Materials and methods

Study area and experimental design

The study area is located in the Xinying catchment of the Changshanling mountain area (27°43' N, 102°13' E), 20 km south of Xichang City, Sichuan province, southwestern China with altitudes of 1450 to 1706 m. The area has a subtropical monsoon climate with a mean annual temperature of 17.1 °C and an annual rainfall of 1013 mm with approximately two thirds of the rainfall occurring between June and October (Yang et al. 2002). The soil was derived from purple sandstone that is easily eroded, and it has a mean depth of 30 cm. The soil texture is generally silty loam.

The original forest on these hillslopes was lost due to tree-cutting for “steel making” in 1958. The present dominate vegetation in the forested hillslope was trees (*Pinus massoniana* Lamb) and shrubs (*Camellia oleifera* Abel) air-planted during the 1970's, and warm season native grass (*Eulaliopsis*) (Table 1). *Pinus massoniana* is a common tree species in plantation forestry areas to replace or compensate for natural forest loss in southern China. It is an evergreen coniferous tree

with a height of 2–8 m, a broad, rounded crown of 2 to 5 m in diameter, and a scaly, plated trunk. The shrub *C. oleifera* with upright, multiple trunks and branches, and oval vase crown reaches a height of less than one meter. The grass *Eulaliopsis* is an upright, dense-tuft perennial species, which has predominantly fibrous roots (Liu 2006). Shrubs and grasses as the understory of the forest serve as contact cover. Root biomass with diameter <2 mm increased in the order of tree < shrub < grass, whereas coarse roots with diameter >2 mm followed the inverse trend (Table 1). Shallow soil layers (30 cm) restrict plant root growth in the forested hillslopes and over 50 % of roots were concentrated in 0–20 cm soil depth.

Frequent human activities (mainly the extraction of litterfall) and grazing by open-raising sheep and cattle have occurred in the forested area (Table 2). Grazing had resulted in the degradation of understory on the hillslope forest, which was increased in areas closer in proximity to the village. Based on different degrees of animal grazing and litter extraction established through discussion with farmers and a field survey, we selected four complete hillslopes representing four levels of understory-degradation: no understory-degradation (control), light understory-degradation, intermediate understory-degradation, and high understory-degradation. As shown in Table 2, the four hillslopes had similar slope degree (19.5–21.9°) and slope aspects (109–113°). To increase the variation in understory-vegetation and channel density in favor of the establishment of vegetation-channel density model, each hillslope was divided into three sections: upper, middle and lower for sampling and observation. The assumption of variations in understory-vegetation and channel density among slope positions is sound, as the slope position can affect the accessibility to people for litterfall extraction and animals for grazing. The four hillslopes had no foothills or significant depositional zones.

Table 1 Growth characteristics of each vegetation type and its contribution to total root biomass in forested hillslopes of southwestern China

Type	Species	Crown width	Diameter ^a	Height	Root biomass distribution	
					Diam.<2 mm	Diam.>2 mm
			(m)	(%)		
Tree	<i>Pinus massoniana</i> Lamb	1.8–5.0	0.26–0.69	2.1–8.0	7–9	27–29
Shrub	<i>Camellia oleifera</i> Abel	0.18–0.9	–	0.19–0.84	9–12	26–27
Grass	<i>Eulaliopsis</i>	–	–	0.4–1.0	18–33	11–21

^a It was measured at breast height

Table 2 Hillslopes and positions selected for the study and reasons for understory degradation

Hillslope	Position	Size (m ²)	Slope degree (°)	Aspect (°)	Understory degradation reason
Control (No understory-degradation)	Upper	12×18	21.0	109	Rare grazing or litter extraction
	Middle	14×18	19.6		
	Lower	13×18	18.0		
Light understory-degradation	Upper	16×29	22.9	110	Occasionally grazing or extracting litter at the lower hillslope
	Middle	14×29	23.4		
	Lower	20×29	19.6		
Intermediate understory -degradation	Upper	20×20	21.2	113	Some litter extraction at the lower and middle hillslope
	Middle	20×20	22.1		
	Lower	19×20	19.0		
High understory-degradation	Upper	15×34	22.1	111	Intensive grazing over the entire hillslope
	Middle	16×34	23.6		
	Lower	16×34	19.3		

Measurement and sampling

A passage in the soil with a depth of 2 cm or greater was considered as channel. In each sampling site, we measured the length of all channels using measuring tapes. The channel erosion was expressed as channel density, which was defined as total length of channels within a unit soil surface area (m m⁻²) (Valentin et al. 2005). The width and depth of channels were also measured in the study.

Soil loss rate was estimated by the ¹³⁷Cs fallout technique (Walling and He 1997). Soil cores were collected at the depth of 0–30 cm, which could penetrate the full depth of ¹³⁷Cs profile. The soil core samples were also collected at undisturbed grasslands at the summit of each hillslope as a reference for determining the local input of the ¹³⁷Cs inventory. The reference sites have remained undisturbed for more than 200 years. The soil samples were air-dried and ground to pass through a 2 mm sieve. The subsamples were used to measure the soil moisture for calculating soil bulk density. The activity of ¹³⁷Cs in soil was measured using a hyper pure Ge detector (BE5030) coupled to a multi-channel analyzer (CANBERRA, USA). The ¹³⁷Cs activity was detected at 662 keV peak using counting time over 80,000 s, which provided an analytical precision of ±5 % for ¹³⁷Cs (Li et al. 2006). At each sampling point, the ¹³⁷Cs inventory was calculated as follows: ¹³⁷Cs (Bq m⁻²) = [activity (Bq kg⁻¹) *total weight of oven-dry soil for the entire core (kg)]/ sampling area (m²). Soil loss rate was determined based on the change in the ¹³⁷Cs inventory relative to the reference using the diffusion and migration model in Walling and He (1997).

Vegetation cover was divided amongst four categories: tree cover (>2 m height), shrub cover, and grass and mulch cover. Vegetation cover was determined by the line transect method (Lutes 2002; Allredge and Gates 1985). A long tape with a 10 cm observation interval was used. The length of transects ranged from 12 to 38 m, depending on plot size and transect orientation.

Root density was measured using soil core samples at two depths: 0–15 cm and 15–30 cm. A steel coring device (8 cm diameter) lined with a steel tube (Bipartite root auger) was inserted into the soil using a sledge hammer to obtain soil core samples. Soil coring was conducted in inter-channel areas near trees and shrubs, within grass and bare ground. Three soil cores were taken around a tree or shrub or randomly from grassy areas to be composited as one sample. In each sampling site, there were four root samples from tree, shrub, grass and bared areas. The collection of roots from soil cores and separation into various diameter classes were conducted using the rinsing method as described in Li et al. (1991, 1992). Briefly, soil core samples were placed in a soil sieve of 0.5 mm mesh and rinsed by water to remove the soil. Each root in the sieve was taken out and measured in diameter with a vernier caliper. Then, the roots were grouped into four diameter classes: <1 mm, 1–2 mm, 2–5 mm, 5–10 mm. The roots in each diameter class were then oven-dried at 60–70 °C for 16–20 h and weighed using a digital balance. The root density (mg dm⁻³) for a given vegetation type was calculated as the total root mass within 0–30 cm soil depth divided by the total core volume. The calculation was performed individually for each root size. The total

root density (RD) per root size in a sampling site was the sum of root density of each vegetation type weighted by vegetation cover as below:

$$RD = \sum_{i=1}^4 RD_i * VC_i$$

where *i* is plant type, 1 for tree, 2 for shrub, 3 for grass and 4 for bare; VC ground cover rate of a given vegetation type.

Statistical analysis

Observations and samplings in each sampling site were conducted with four replications, from which mean and SE were calculated. We created one dependent variable (channel density) and eight independent variables that included the densities of four root diameter classes (<1 mm, 1–2 mm, 2–5 mm, 5–10 mm), and covers of four vegetation types (tree cover, shrub cover, grass cover, and mulch cover).

To identify the major vegetation factors controlling channel density, we performed principal component regression (PCR), which could remove multicollinearity among independent variables (Fekedulegn et al. 2002). First, principal component analysis (PCA) was used to transform the original vegetation variables into a new set of variables called principal components, which could explain some variations of the data set. Then, using PCR, we performed a multiple regression analysis of

the response variable (channel density) against the set of principal components of the highest ranking that could totally explain 85 % of variations. Because the principal components were pairwise independent, multiple linear regression procedure was valid. At last, the regression coefficients for the principal components were transformed back to obtain a set of coefficients that corresponded to the original variables to form the channel density - vegetation model.

Results

Channel morphometrics

As shown in Table 3, length, width, and depth of channels in four hillslopes ranged from 0.2 to 25.2 m, 0.03 to 2.2 m and 0.01 to 0.7 m, respectively, and that no channels were observed in control. A 22 and 26 % increase were shown for average length and depth of channels, respectively, from the hillslope with light understory-degradation to that with intermediate understory-degradation. A much greater increase of 460 % (average channel length) and 35 % (average channel depth) was found from the hillslope with intermediate understory-degradation to that with high understory-degradation. Rilling was the dominate channel erosion feature in the three hillslopes with understory-degradation. Gullies were only identified at the middle and upper plots of the hillslope with high understory-

Table 3 Morphometric parameters of channel (rill or gully) at sampling sites of forested hillslopes

Hillslopes	Position	Length (m)			Width (m)			Depth (m)		
		min	max	average	min	max	average	min	max	average
Control (No understory-degradation)	Upper	0	0	0	0	0	0	0	0	0
	Middle	0	0	0	0	0	0	0	0	0
	Lower	0	0	0	0	0	0	0	0	0
Light understory-degradation	Upper	0.1	2.5	1.9±0.1	0.06	0.10	0.09±0.003	0.01	0.11	0.11±0.01
	Middle	0.3	2.0	2.0±0.03	0.05	0.20	0.08±0.001	0.01	0.18	0.09±0.00
	Lower	0.2	3.2	1.2±0.01	0.03	0.08	0.04±0.001	0.01	0.08	0.05±0.01
Intermediate understory-degradation	Upper	0.6	3.1	2.2±0.1	0.63	2.0	1.01±0.05	0.05	0.28	0.14±0.01
	Middle	1.0	3.0	2.2±0.1	0.56	1.4	0.80±0.03	0.05	0.29	0.12±0.01
	Lower	0.7	3.0	2.0±0.1	0.45	1.1	0.71±0.02	0.03	0.17	0.07±0.00
High understory-degradation	Upper	3.3	25.2	11.3±2.0	0.31	2.1	0.89±0.05	0.03	0.70	0.17±0.02
	Middle	3.0	23.0	11.2±1.8	0.30	2.2	0.88±0.06	0.04	0.54	0.16±0.02
	Lower	3.0	22.5	12.3±1.8	0.20	1.1	0.56±0.08	0.02	0.30	0.11±0.03

degradation, where a small number of channels were deeper than 0.3 m.

Channel density and soil loss rate

The four different hillslopes had great variability in channel density (Table 4). The forested hillslope with high understory-degradation had the largest channel density ($0.31 \pm 0.05 \text{ m m}^{-2}$). The forestland with intermediate understory-degradation had a slightly lower channel density ($0.23 \pm 0.03 \text{ m m}^{-2}$). The hillslopes with either light or no understory-degradation had channel densities of $0.12 \pm 0.06 \text{ m m}^{-2}$ and 0 m m^{-2} , respectively. Thus, channel densities in the intermediate and high understory-degradation forestlands were 2 and 2.6 times greater, respectively, than those of light understory-degradation forestland.

Distinctive spatial patterns in channel density were also observed at various points of a hillslope (Table 4). Channel density for the middle and lower plots of the hillslope with high understory-degradation were 77 and 60 % greater than that for upper plots ($0.21 \pm 0.00 \text{ m m}^{-2}$), respectively. Among intermediate understory-degradation hillslope, channel density increased by 10 to 42 % from the upper plot (0.20 m m^{-2}) through the middle plot to the lower plot. In contrast, channel densities for the hillslope with light understory-degradation forestland had values ranging from 0.11 to 0.13 m m^{-2} which did not vary significantly at different points along the hillslope.

Based on ^{137}Cs analysis, the potential soil loss rate ranged from -2.3 to $0.1 \text{ Mg ha}^{-1} \text{ year}^{-1}$ at the control hillslope, -2 to $4 \text{ Mg ha}^{-1} \text{ year}^{-1}$ at hillslopes with light understory-degradation, -0.1 to $12 \text{ Mg ha}^{-1} \text{ year}^{-1}$ at hillslopes with intermediate understory-degradation, and 71 to $143 \text{ Mg ha}^{-1} \text{ year}^{-1}$ at hillslopes with high understory-degradation (Table 4). The results show that channel density among four slopes and slope positions generally increased with the increase in soil loss rate.

Vegetation cover

Vegetation cover varied considerably among the four hillslopes and the three positions (Table 4). The forestland with high understory-degradation had the smallest cover by all other vegetation types. Hillslopes with intermediate understory-degradation had the most extensive tree cover (65 %) and smallest shrub (9 %) and grass cover (21 %), as compared to those with light or no

understory-degradation. The light understory-degradation hillslope had shrub and grass covers of 19 and 65 %, and no understory-degradation hillslope had shrub and grass covers of 28 and 97 %. These percentages were four to six times (shrub cover) and five to seven times (grass cover) greater than respective values for the high understory-degradation hillslope. Mulch cover was found to be high relative to other vegetation types (ranging from 64 to 76 %) for most hillslopes, except in areas of high understory-degradation (31 %).

Tree cover slightly increased from the middle to downslope on hillslope with intermediate understory-degradation (Table 4). A decreasing trend (33 to 55 %) for mulch cover was found downslope on high and light understory-degradation hillslopes. In contrast, mulch cover on the hillslope with no understory-degradation showed a significant downslope increase (169 %). Shrub cover on the high understory-degradation hillslope increased downslope by a factor of 1.9 times, while a decreasing trend was identified from the upper to lower positions on the other three hillslopes. Grass cover decreased by 32 % from the upper to lower positions on the intermediate understory-degradation hillslope. No significant variations along slope in grass cover were observed for hillslopes with light and no understory-degradations.

Channel density was found to be more strongly related to grass and shrub cover (Fig. 1a & b). There was no significant correlation between channel density and tree and mulch covers. Channel density decreased with the increase in grass and shrub cover according to a logarithmic regression equation. The inverse relationship between channel density and grass cover appears to function discretely (Fig. 1a). The channel density decreased rapidly when grass cover increased from 10 to 30 %. For grass cover values above 30 %, channel density decreased more gradually. The relationship between channel density and shrub cover indicates that shrub cover values of more than 20 % would cause a sharp reduction in channel density (Fig. 1b). Relative to grass cover, shrub cover appears to exert a stronger influence in reducing channel density.

Root density

Total root density in forested hillslopes was found to decrease along with the increase in understory-degradation (i.e. no, light, intermediate and high understory-degradation) based on data in Table 4. The

Table 4 Vegetation coverage, root density, channel density and soil loss rate at sampling sites of forested hillslopes (mean±SE)

Slope	Position	Channel density m m ⁻²	Soil loss rate ^a Mg ha ⁻¹ year ⁻¹	Root density				Vegetation coverage			
				<1 mm	1–2 mm	2–5 mm mg dm ⁻³	5–10 mm	Tree	Shrub	Mulch	Grass
Control (No understorey-degradation)	Upper	0.00	-1.60±1.24	337±21.9	60.3±6.04	51.0±2.71	12.7±11.5	14.6±0.1	27.6±0.1	32.6±0.2	98.2±0.0
	Middle	0.00	0.14±3.35	441±31.7	46.9±5.63	323±64.9	92.1±11.0	36.5±0.1	29.9±0.1	70.3±0.0	97.9±0.0
	Lower	0.00	-2.25±1.74	375±12.1	173±10.7	36.2±5.49	379±49.7	26.8±0.1	25.5±0.1	87.6±0.0	93.9±0.0
Light understorey-degradation	Upper	0.13	-2.10±3.43	206±32.2	49.8±10.6	79.4±27.9	50.9±36.6	35.7±19.1	18.8±6.6	83.0±9.3	68.6±8.7
	Middle	0.12	0.80±3.07	200±33.0	55.3±15.5	54.4±9.17	0.0±0.0	48.4±11.3	27.1±7.1	89.0±5.1	58.3±14.8
	Lower	0.11	4.14±3.55	165±9.84	26.4±7.40	39.2±11.7	16.5±2.14	22.4±16.2	11.7±7.6	56.7±15.2	67.7±6.8
Intermediate understorey-degradation	Upper	0.20	-0.07±4.03	110±8.15	15.1±2.36	26.7±5.73	25.1±4.01	64.0±27.5	8.0±4.9	73.1±8.9	23.2±5.8
	Middle	0.22	7.16±4.35	53.4±10.6	6.7±1.00	19.2±3.06	16.4±2.62	58.9±17.3	11.6±7.1	78.2±7.0	22.4±8.0
	Lower	0.28	12.0±4.15	41.5±8.90	12.3±1.68	31.5±5.03	19.2±3.07	67.6±17.3	7.3±5.2	73.1±4.1	15.3±7.6
High understorey-degradation	Upper	0.21	142±0.00	51.4±9.39	29.3±3.32	30.2±7.06	11.0±1.47	8.2±8.4	3.6±2.0	34.2±4.7	11.7±4.9
	Middle	0.38	143±0.00	53.7±8.96	8.4±11.3	35.3±8.20	93.1±29.1	9.2±7.3	5.3±3.0	42.9±5.2	16.2±4.9
	Lower	0.34	70.6±39.0	41.1±7.76	7.7±5.68	16.7±7.23	10.2±1.30	9.7±7.3	6.3±3.6	17.1±2.5	11.6±2.9

^a Positive values indicate soil erosion (loss), and negative values soil deposition (gain)

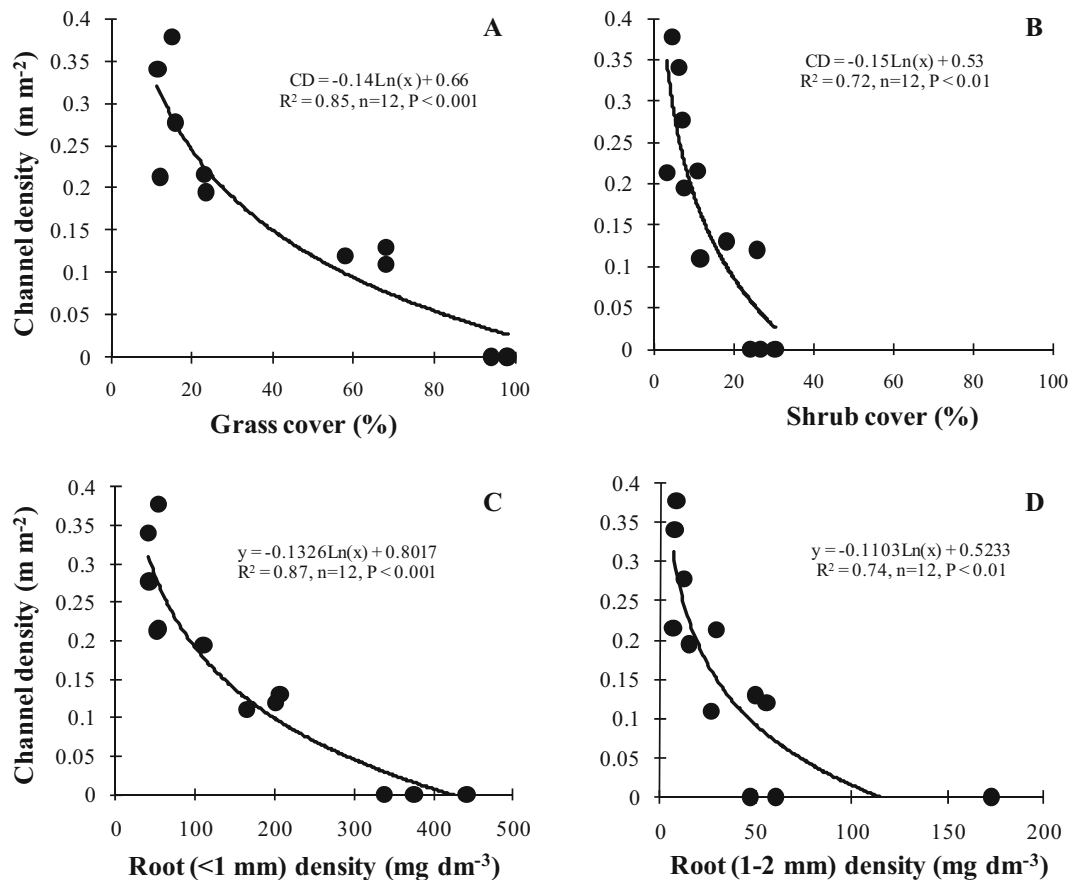


Fig. 1 Simple correlation between channel density and vegetation variables at forested hillslopes of southwestern China, which is significant at $P < 0.05$ level. CD stands for channel density

decrease in root density along with the understory degradation in forested hillslope found to be most pronounced for fine root (<1 mm). Total root density values for all root diameter classes were observed to decrease from the upper slope portions of the hillslope to the middle and lower slope positions. Total root density decreased by around 39–50 % from the upper slope positions to the lower portions on hillslopes with light, intermediate and high understory-degradation. In contrast, on the no understory-degradation hillslopes, root density values showed an increasing trend downslope.

Channel density decreased with fine root (<1 mm) density with a piecewise relationship of three discrete domains (Fig. 1c). When fine root density increased from 24 to 140 mg dm^{-3} , channel density decreased by 60 %. At fine root density between 140 and 320 mg dm^{-3} , channel density decreased from 60 to 90 % as compared to that at fine root density of 24 mg dm^{-3} . For fine root density greater than 320 mg dm^{-3} , channel density decreased at an

extremely low rate. Channel density sharply declined with the increase in root density for diameter 1–2 mm (Fig. 1d). No significant correlation was found between channel density and root density of diameters 2–5 mm and 5–10 mm.

Principal component regression

The vegetation variables as independents for predicting the channel density (dependent) were correlated themselves (colinearity) (Pearson' correlation coefficient not shown), and thus, principal component analysis/regression was used to identify vegetation variables that have significant influence on channel density. The principal component analysis (PCA) showed principal component (PC) 1, 2 and 3 were important as they had eigenvalues of above 1.0 (5.20 for PC1, 1.67 for PC2, and 1.30 for PC3). The first principal component (PC1) accounted for 57.7 % of the total variation of the eight vegetation variables. In PC1, the vegetation variables

that had loadings of above 0.4 were fine root (<1 mm) density, shrub cover and grass cover (Table 5). We interpreted PC1 as the overall soil resistance to concentrated flow supported by enlacing of fine roots and rainfall interception by shrub and grass cover. The second principal component, which accounted for 18.6 % of the total variation of the eight vegetation variables, was controlled by tree cover and mulch cover. The PC2 can be interpreted as the measurement for concentrated runoff caused by stem flow and densely formed mattress of pine needles. The third principal component, which accounted for 14.4 % of the total variation of the eight vegetation variables, can be considered as the root tensile strength of coarse roots.

Principal component regression (PCR) was then performed to determine if all three PCs should be included in the prediction of channel prediction as: $y = a + bPC_1 + cPC_2 + dPC_3$. The regression results indicate that only PC1 had a *t*-value with $P < 0.05$ (Table 6), and thus only PC1 could be included in the prediction of channel density. Since the major contributing factors for PC1 were fine root density, shrub cover and grass cover, these three factors largely related to understory are most important in controlling the channel initiation in forested hillslopes. Other factors such as tree cover and mulch cover in PC2 and coarse roots in PC3 would have no major influence on the channel density in forested land. After PC coefficients were transformed to those for original vegetation variables listed in Table 5, we obtained the channel density prediction model as $y = 9.021 -$

Table 5 Principal component (PC) with eigenvalues above 1.0 and loadings of vegetation variables on a PC

Variable	PC1 ^a	PC2	PC3
X1 (RD <1 mm diam.) ^b	0.4578	-0.1363	0.1486
X2 (RD 1–2 mm diam.)	0.3924	-0.0607	-0.4823
X3 (RD 2–5 mm diam.)	0.2727	-0.0577	0.6151
X4 (RD 5–10 mm diam.)	0.3461	0.0372	-0.5254
X5 (tree cover)	0.0093	0.7421	0.1461
X6 (shrubs cover)	0.434	-0.0217	0.2283
X7 (mulch cover)	0.241	0.6345	-0.0655
X8 (grass cover)	0.4424	-0.1387	0.1146

^a PC principal component

^b RD root density

^c Bold indicates the loading is above 0.4, the standard for a key contributor in PCA analysis

Table 6 Regression of channel density against the principal components

Variable	Parameter estimate	<i>t</i> value	Pr> <i>t</i>
Intercept	5.75E-16	3.96E-15	1.00
PC1	-0.427	-5.92	0.000354
PC2	0.035	0.299	0.772
PC3	-0.085	-0.636	0.543

$$0.018X1 - 0.019X2 - 0.019X3 - 0.01X4 + 0.002X5 - 0.066X6 - 0.015X7 - 0.034X8 \quad (R^2 = 0.82, P < 0.001).$$

Discussion

In this study, we found that channel density in the forested hillslope was inversely related to grass and shrub covers and fine root density. This supports the hypothesis that forested hillslopes lacking of grass and shrub cover (understory) and fine roots are vulnerable to soil erosion. The increase in channel erosion and soil loss from light to high understory-degradation hillslopes was clearly associated with the low understory cover and fine root density. This effect is also evident in variations in understory cover, fine root density and channel erosion with different slope positions. For hillslopes with understory degradation in this study, understory cover and fine root density were generally lower from the upper to lower slopes. In a hillslope, the lower slope is easily accessible to people and animals, resulting in higher litter extraction and grazing, respectively (Table 1). Thus, the increase in channel density and soil loss from the upper to lower slopes could be explained by the increase in understory degradation driven by better accessibility to human activities and animals grazing.

Loss of vegetation cover and removal of leaf litter led to the formation of soil seals (Singer and Bissonnais 1998) and exposure of soil particles to the direct impact of raindrops (Mohammad and Mohammad 2010), both of which enhance runoff and soil erosion (Descroix et al. 2001, 2008; Snyman and duPreez 2005; Al-Seikh 2006). Overgrazing and cattle movement were the main causes of gully erosion in mountainous areas (Descroix et al. 2008). Models described here showed that dwarf shrub cover and grass cover were more effective than tree cover in preventing channel initiation, indicating that the type of vegetation is an important factor to

erosion control. Although tree cover intercepts rain droplets (Coppin and Richards 1990; Simon and Collison 2002), it may not be effective for coniferous species. Pine needles above ground divert rain droplets, and the narrow-shaped and densely interlaced pine-needle mattress on the soil surface decreases the water infiltration capacity. Pine species in this study mainly serve to concentrate surface runoff from stem flow. Nunes et al. (2011) also reported serious runoff and soil erosion from land afforested with pines in Portugal. In such coniferous forests, the understory is especially important for controlling soil erosion. Even in situations where the forest is established on the hillslope, if there is understory degradation, soil erosion would still pose a problem. This issue needs to be taken into consideration in reforestation planning and assessment. In forestlands, overgrazing and litterfall extraction should be avoided or minimized to ensure adequate understory for controlling soil erosion.

The significant inverse relationship between fine root (<1 mm) density and channel density revealed in the study further emphasizes the role of fine roots in controlling soil erosion by concentrated flow, which was initially observed in laboratory and plot experiments (Li et al. 1991; Gyssels et al. 2005). Using the flume method, Li et al. (1991) found that the ability of plant roots to mitigate concentrated flow erosion mainly depended on the presence and distribution of ‘effective’ roots (<1 mm) in the top 50 cm of the soil. Gyssels et al. (2005) showed that while dense root systems produced by a mix of small trees, shrubs, and grasses were important in maintaining slope stability, shallow dense root networks produced by grasses appear to be more effective in protecting soils from water erosion by concentrated flow. It is also the case that fine and small roots (0.5–2.0 mm in diameter) at deeper soils (root depth >30 cm) with high tensile strength, especially for tree species, are more efficient in supporting stream bank stability (Davidson et al. 1989; Wynn et al. 2004; Wynn and Mostaghimi 2006). The grasses and shrubs are optimum cover types for slope stabilization largely due to their large numbers of small, strong roots (Li. 1995; Dabney et al. 1997). Thus, shallow and densely distributed fine roots (root depth <30 cm), especially for herbaceous species, played the most important role in control of channel initiation by concentrated overland flow. De Baets and Poesen (2010) reported the erosion-reducing effect by roots was well explained by fibrous roots, but not tap roots. Li (1995) reported that only fine roots (<1 mm) can

effectively contribute to the improvement of soil non-capillary porosity and the formation of water-stable aggregates of 2–5 mm and >5 mm. The fine roots generally have larger surface area than coarse roots, and this might have allowed fine roots to have greater binding ability in the aggregate formation. Although fine roots were apparently the most important variable in controlling soil erosion in forested hillslopes, our results also showed some contribution of coarse roots in reducing the channel density, and thus they should also be considered in soil erosion control. Simon and Collison (2002) found most of the root strength under woody species came from larger (>5 mm diameter) roots.

The majority of previous studies have addressed the role of plant roots and vegetation cover separately in affecting soil erosion (Li et al. 1991; Flanagan and Nearing 1995; Renard et al. 1997). This study has integrated the combined influence of root density and shrub and grass vegetation covers on channel density in the forested land in a single model. The model generated can be used for predicting channel density and evaluating soil erosion in forested hillslopes.

Conclusions

Based on the results from this study, we conclude that plant fine roots (<1 mm) and grass and shrub vegetation cover are major factors in determining soil erosion in forested hillslopes in southwestern China. In hillslope afforested with coniferous species, maintenance of a good understory through reduction of grazing and litter extraction is crucial for controlling soil erosion. Understory with 60 % grass coverage and 20 % shrub coverage is needed to prevent channel initiation in forested hillslopes. The model generated from this study using principle component regression can be applied to assess channel erosion in forestland in southwestern China and other similar sites in other regions. Our results suggest that quantification of fine root along with grass and shrub covers in forested hillslopes would be needed to assess the role of Chinese reforestation in soil erosion control and in understanding the mechanism of channel initiation in forestland.

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