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Full Length Research Paper

Responses of surface soil carbon and nutrients to re-vegetation of an eroded hillslope in southwest China

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Chinese national re-vegetation on the eroded hilly landscapes may have potential to modify the surface soil carbon (C), nitrogen (N) and phosphorus (P) pools. However, few studies have investigated this relationship. We quantified differences in soil organic carbon (SOC), soil available nitrogen (AN), available phosphorus (AP), and soil bulk density (BD) of the surface soil (0 to 10 cm) among different types of vegetation cover (VC) and slope positions on a re-vegetated hillslope that was previously used as farmland at Xichang, Southwestern China. The four different VC types examined in this study were: a) tree, b) shrub, c) grass and d) bare soil. SOC, AN and AP under vegetation cover, whether tree, shrub, or grass, were higher than that in the bare soil. SOC, AN and AP were highest under shrub and grass followed by tree cover. SOC stock under tree, shrub and grass cover were respectively 1.76, 3.50 and 3.71 times the stock in bare soil, whereas AN concentration was 1.02, 2.60, and 1.39 times the concentration in bare soil. Moreover, AP concentration in soils under tree, shrub and grass cover was 3.91, 5.48 and 6.69 times the concentration in bare soil, respectively. Soil bulk density under shrub and tree cover was slightly lower (11 and 6%, respectively) than that in the bare soil, but not for the soil under grass cover. The relationship between surface SOC, AN, BD and vegetation cover types is irrespective of hillslope positions (excepting a significant higher AP concentration at the lower slope than the top of the hillslope), suggesting a link to re-vegetation. Our results therefore indicate that re-vegetation, specifically with shrubs and grasses, could contribute to ecological restoration of eroded hillslope through modifying surface SOC and nutrients, and hence improving soil quality in southwest China.

Key words: Re-vegetation, soil organic carbon, soil nutrients, soil bulk density, eroded hillslope.

INTRODUCTION

Accelerated soil erosion in hilly regions of Southwest China is considered a major contributor to land degradation and sediment-associated nutrient inputs to the Upper Yangtze River. This accelerated soil erosion is primarily the result of intensive tillage and livestock grazing activities that reduce vegetation cover and result in a loss of surface soil and a deterioration of soil quality (Valentin et al., 2005). Over the last decade, a large re-vegetation project for the restoration of eroded hillslopes in Western China, locally known as the “grain-for-green” policy, was designed to shift about 15 million ha of low-yielding farmland to forestland and to afforest another 17 million ha of barren mountains (UNCCD, 2002; Feng et al., 2005). The restoration of eroded areas through re-vegetation including the planting of trees/shrubs and grasses on previously cultivated hillslopes and fenced

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Abbreviations: SOC, Soil organic carbon; **AN,** soil available nitrogen; **AP,** available phosphorus; **BD,** soil bulk density; **VC,** vegetation cover.

grassland has been conducted throughout the northern and western regions of China. Research is therefore needed to quantify effects of this national re-vegetation project on soil erosion and soil quality though there has been little monitoring of these efforts.

One benefit of re-vegetation on eroded hillslopes would be an increase in soil organic carbon (SOC) pools. This increase is essential to nutrient balance and soil quality improvements because SOC plays an important role in storing water, nutrients and microbial energy, and also promoting soil aggregation (Fettweis et al., 2005; IPCC, 2001; Jens, et al., 2005; Lal, 1999). In restoring eroded hilly agro-ecosystems, many mechanisms influence soil organic carbon pools. For example, the plant used for re-vegetation (grass, shrubs or trees) provides a protective biomass surface over the soil and a distributed root biomass network in the soil that enables the development of biopores important in many soil and plant functions (De Baets et al., 2007; McClaran et al., 2008). Plants produce leaf litter which supports a wide range of micro and macro decomposers that are surely important for cycling nutrients, creating SOC and developing soils, especially on eroded surfaces (Wheeler et al., 2007). In the overgrazing areas, plant roots may play more important role in increasing SOC through holding the soil in position and preventing it from being blown or washed away (Li et al., 2006b). The increased SOC and available nitrogen (AN) and available phosphorus (AP) through re-vegetation has many implications for both soil quality improvement and erosion control (Li and Lindstrom, 2001).

The surface layer is considered a critical component of agro-ecosystems and contains the most important C, N and P pools of the soil profile (Franzluebbers and Brock, 2007). The impact of land use or management on profile C and N pools occurs primarily in the surface (depth of 0 to 15 cm) soil (Franzluebbers and Stuedemann, 2003, 2005, 2008; Blanco-Canqui and Lal, 2008; Novak et al., 2009). Hence, the changes in surface soil C, N, and P fractions are likely to be sensitive to vegetation reestablishment. Although there are many studies on the effects of re-establishment of vegetation in enhancing the resistance of soil to overland flow erosion in the Chinese Plateau (Li et al., 1992a, 1992b; Li and Lindstrom, 2001), few studies have been conducted on their impacts on surface soil C, N and P pools on the eroded hilly landscapes. Knowledge of changes in these pools with a transition from cropland to forestland and grassland is needed to understand ecological impacts of Chinese national re-vegetation projects.

In this study, we evaluated the effects of different vegetation cover types (tree, shrub, and grass) and slope positions on the surface (0 to 10 cm) SOC, AN, AP, nutrients and bulk density (BD) to improve our understanding of changes in soil quality on eroded hillslopes. As part of a re-vegetation project, this information on soil quality parameters will lead to better management of these soils for improved environmental quality.

MATERIALS AND METHODS

Study hillslope

Field sampling was conducted on an eroded hillslope of the Majiasongpo watershed (1549 to 11615 m a.s.l, 27°43′ N and 102°13′ E.) 23 km south of Xichang City in southwestern China. The Majiasongpo watershed has a subtropical monsoon climate. Long-term mean temperature is 17.1°C and precipitation is 1013 mm, with approximately two thirds of the annual rainfall distribution from June to October (Yang et al., 2002). A detailed topographic survey was carried out on the study hillslope (Figure 1). The elevation of the hillslope is 54 m, hillslope gradients are 9.8, 12.2, 14.1 and 3.6° at the top, upper, middle and lower positions, respectively. The soils in the study area, derived from purple stone, are classified as regosols in the Food and Agriculture Organization of the United Nations (FAO) soil taxonomy. The surface soil is silt-loam texture with 25.9% clay, 44.8% silt and 29.3% sand, and is potentially erodible, especially under conditions of no vegetation cover.

The study hillslope was lightly terraced in the early 1950s and since then had been used for farmland until the implementation of the national re-vegetation project in 1970s. Thereafter, this hillslope had been somehow interrupted by human activities, such as grazing, trampling and collecting leaf litters under trees. Different vegetation types do not overlap and coexist on the study hillslope, which characterizes the ecological forests used for soil erosion control in Southwest China.

The dominant vegetation covers present on the hillslope include trees (*Eucalyptus* and *Pinus massoniana* (Lamb)), shrubs (*Camellia oleifera* (Abel)) reestablished in 1970s through air-flight seeding under the national re-vegetation project and native grass (*Eulaliopsis binata*). These species have colonize eroded hillslopes in many parts of Xichang area in southwestern China.

The current ground cover was surveyed along five transects with the shape '✳' across each slope position by the line transect method using a long tape and a 10 cm observation interval. The surveyed results showed ~9% tree, ~19% shrub, ~31% grass and ~41% bare soil on the study hillslope. Soil organic carbon and nutrient contents in the former cultivated hillslopes before re-vegetation were very low due to severe water erosion and uniformly distributed at the same slope positions due to intensive tillage operation. Thus, the conversion of forestland from farmland may result in heterogeneous soil properties across the study hillslope due to different vegetation cover types, although the initial values of SOC and nutrient contents were unknown in the farmland before the land use change. Given the bare soil on the investigated hillslope has been always suffering severe water erosion, it could be used as a comparison with the soils under different vegetation cover types to assess the effects of re-vegetation on soil properties.

Soil sampling

The differences in SOC, nutrients and BD among different vegetation cover (VC) types were documented from soil cores taken on the surveyed hillslope in April 2004 (Figure 1) using a 6.7 cm diameter hand-operated core sampler driven by hammer. For conducting soil coring under different VC types, three individual trees and shrubs, and three grassy areas and bare ground spots were randomly selected, respectively, within the top, upper, middle and lower portions of surveyed hillslope. Three soil cores taken from 0 to 10 cm depth were collected beneath canopies of each

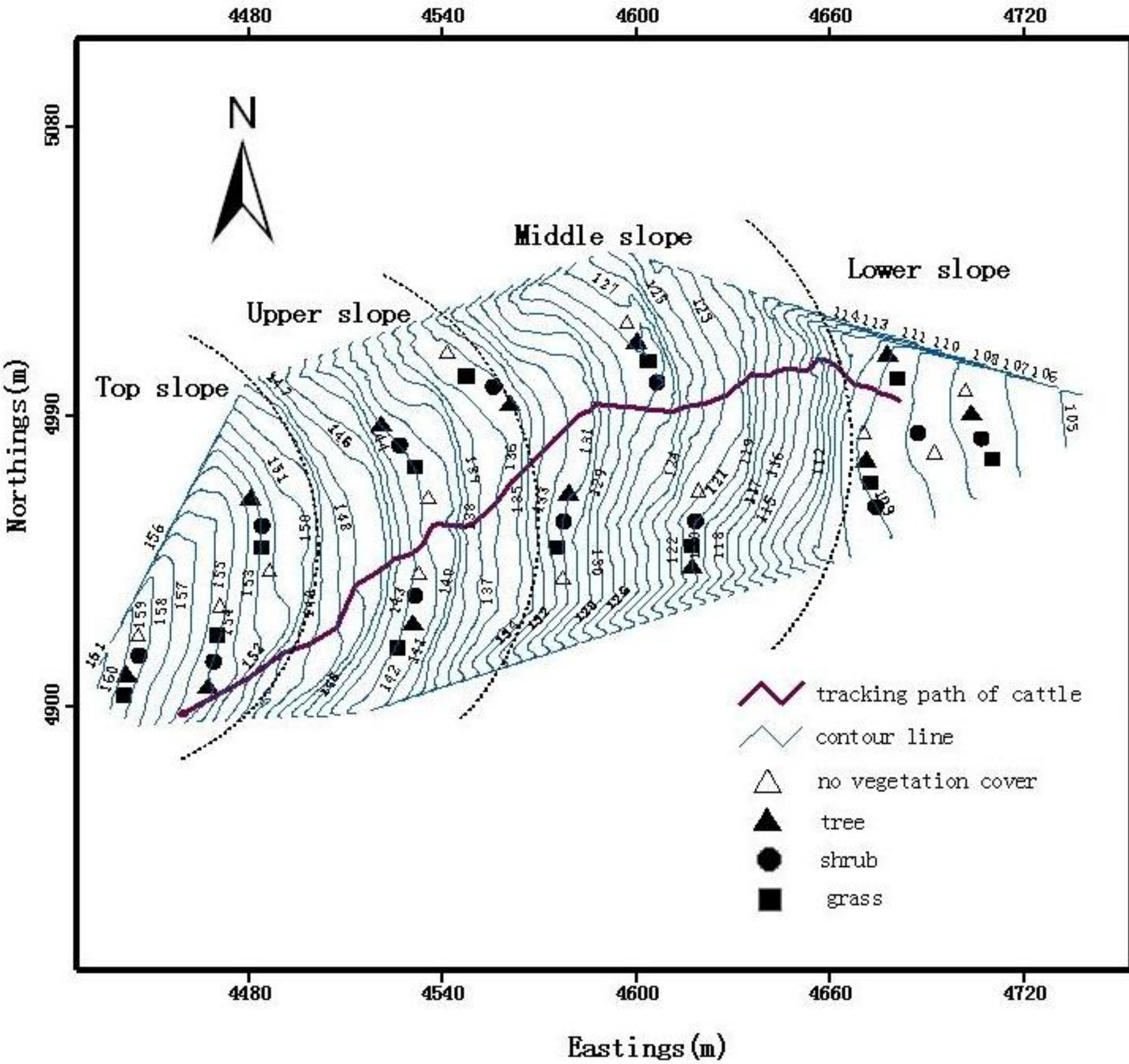

Figure 1. A contour map of the study hillslope and schematic diagram showing sampling points under different vegetation cover types and slope locations in the Majiasongpo watershed, Southwestern China.

tree and shrub, or within grass and bare ground. These three cores were bulked to one composite sample for determination of SOC, AP and AN contents and BD. We collected a total of 48 composite soil samples from the entire hillslope (Figure 1).

Laboratory analysis

Soil samples were air-dried, weighed, and divided into two parts, one passing through a 0.15 mm sieve for the measurement of SOC, and the other passing through a 0.25 mm sieve for the measurements of AN and AP. The total SOC concentration was determined by the dry combustion method (1500°C) with Auto TOC/TN Analyzer (multi N/C 3000, analytic/Jena, Germany; Nelson and Sommers, 1996). Three replicates were analyzed and results recorded for each soil sample. The total amount of organic carbon (SOC, t C ha^{-1}) stored in the surface 10 cm was calculated as follows:

$$SOC = BD \times SOC_c \times D \quad (1)$$

Where, SOC_c is the soil organic carbon concentration in units of g.kg^{-1} of soil dry mass, *BD* is soil bulk density in units of g cm^{-3}, and D is soil sampling depth in units of cm. The BD was determined from the volume of bulked soil cores over the 10 cm sampling depth and oven-dried soil mass (Li and Lindstrom, 2001).

Available P (mg kg^{-1}) in soil was determined by sodium bicar-

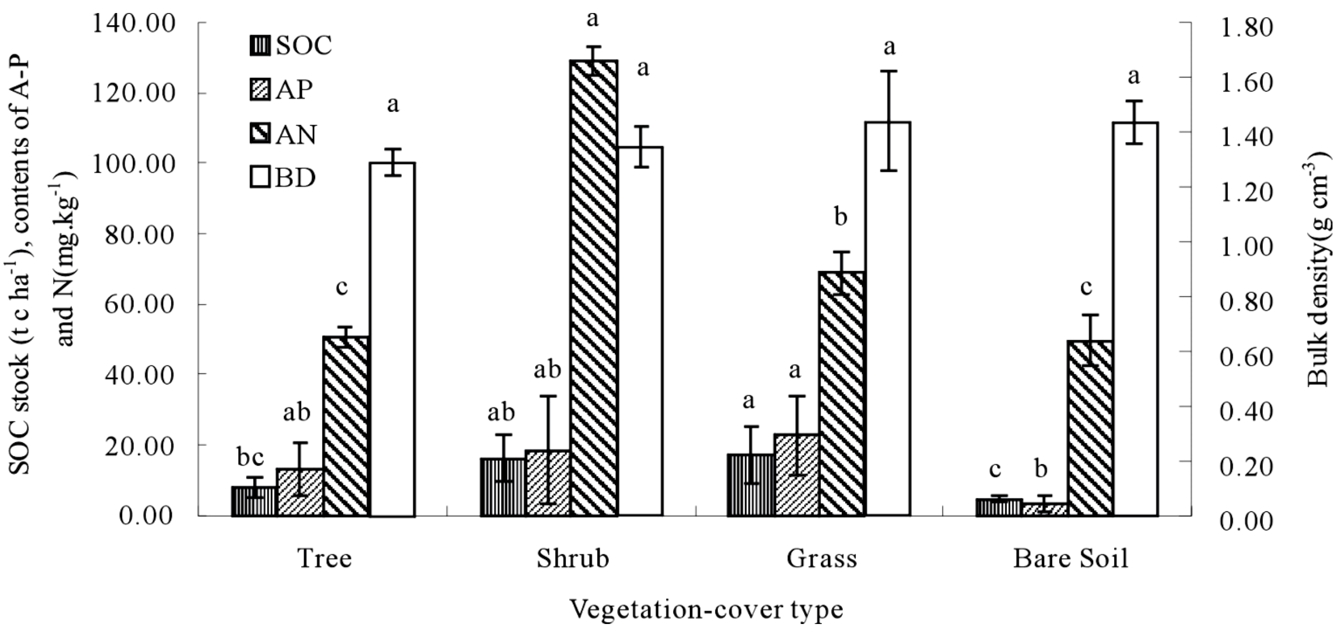

Figure 2. SOC stocks (t C ha^{-1}), available N (AN, mg kg^{-1}), available P (AP, mg kg^{-1}) and soil bulk density (BD, g cm^{-3}) in surface soil (0 to 10 cm) grouped by vegetation cover types. Bars are standard deviations of the means. Different letters carried by bars indicate significant differences in vegetation cover types at p<0.05, n = 12. SOC, Soil organic carbon.

bonate ($NaHCO_3$) extraction and subsequent colorimetric analysis (Olsen et al., 1954). Available nitrogen in soil (mg kg^{-1}) was determined by using a micro-diffusion technique after alkaline hydrolysis (Bao, 2000). All analysis was conducted in the Soil Quality Laboratory at the Institute of Environment and Sustainable Development in Agriculture, Beijing.

Data analysis

Differences in SOC, AN, AP and BD among different vegetation cover types and among different slope positions were explored using a single way analysis of variance and the least significant difference (LSD) method for comparisons. All statistical analyses were performed with the SAS statistical package (SAS 9.1, SAS Institute, Cary, NC, USA, 1990).

RESULTS

Soil organic carbon (SOC)

Figures 2 and 3 summarize the changes in soil quality parameters grouped by vegetation cover types and hillslope positions. As can be seen, SOC stocks at 0 to 10 cm depth varied among different vegetation cover types with the following decreased order: grass > shrub > tree >bare soil. SOC stocks under grass cover were slightly higher than under shrub cover, but significantly higher ($p<0.05$) than under the tree cover. SOC stocks under tree, shrub and grass cover were respectively 1.76, 3.50 and 3.71 times the stocks in bare soil. In contrast, SOC stocks had no significant changes among different slope positions, although SOC stocks were higher at the top slope position than other slope positions of the surveyed hillslope (Figure 3).

Available nitrogen (AN)

Similar to SOC stocks, AN contents in soils under shrub and grass cover were significantly higher (p<0.05) than the tree cover and bare soil, whereas slope position did not have significant effects on AN on the surveyed hillslope (Figures 2 and 3). The AN concentrations in soil surface (0 to 10 cm) among different vegetation cover types decreased in the following order: shrub >grass > tree = bare soil. The AN content under shrub and grass cover was 2.60 and 1.39 times the content, respectively, in both bare soil and the soil under tree cover. As can be seen from Figure 3, there were no significant differences in AN content in soil among different slope positions of surveyed hillslope, although there were slightly lower AN content at the upper slope position than other portions of the hillslope.

Available phosphorus (AP)

Unlike SOC and AN, the differences in AP contents in soil surface (0 to 10 cm) were not significant under different vegetation cover types, whether grass and shrub or tree, although AP contents increased in the following order: tree < shrub < grass. AP contents in the bare soil was extremely small with a mean value of 3.38 mg kg^{-1} over the entire surveyed hillslope and significantly lower than

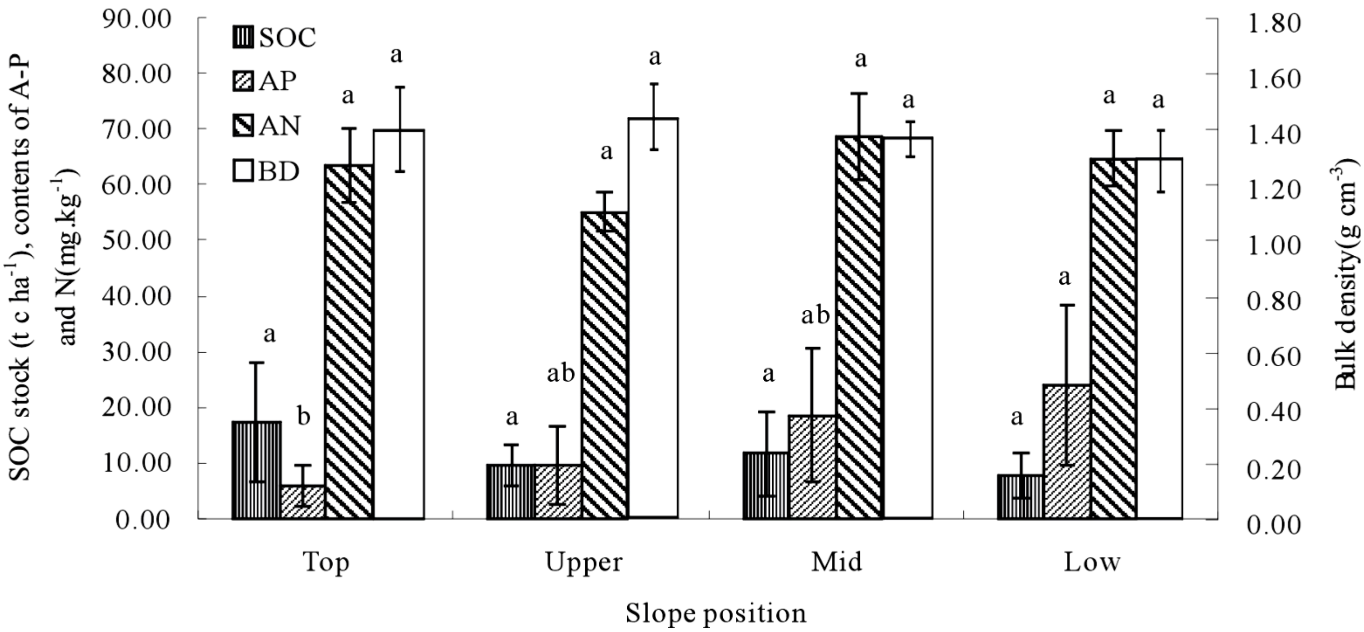

Figure 3. SOC stocks (t Cha^{-1}), available N (AN, mg kg^{-1}), available P (AP, mg kg^{-1}) and soil bulk density (BD, g cm^{-3}) in surface soil (0 to 10 cm) grouped by slope positions. Bars are standard deviations of the means. Different letters carried by bars indicate significant differences in slope positions at $p<0.05$, n = 12. SOC, Soil organic carbon.

in the soil under vegetation cover (Figure 2). AP contents in soil under grass, shrub and tree cover were 6.69, 5.48 and 3.91 times the contents in the bare soil, respectively. In contrast, AP contents in surface soil increased in the down hillslope direction in the following order: top slope < upper slope < middle slope < lower slope (Figure 3). AP contents in soil at lower, middle and upper slope positions were 4.12, 3.20 and 1.63 times the contents at the top slope position of the surveyed hillslope, respectively.

Bulk density (BD)

Comparisons of BD in the soil surface under different vegetation cover types indicated that BD under shrub and tree cover was lower than under grass cover. BD in the soil under grass cover was the same as bare soil (1.43g cm^{-3}) and 11 and 6% higher than those under shrub cover (1.28 g cm^{-3}) and tree cover (1.35 g cm^{-3}). Like SOC and AN, slope position did not have a significant effect on surface BD, although a slight higher BD at the top position than other slope positions of the surveyed hillslope.

DISCUSSION

The SOC, AN and AP in the soil surface under vegetation cover, whether tree, shrub, or grass, are much higher than in bare soil of the surveyed hillslope irrespective of slope positions (Figures 2 and 3). These results suggest a significant positive role of vegetation reestablishment in improving soil quality parameter of the eroded hillslopes, whereas much lower soil nutrients on the studied hillslope of southwest China was mostly caused by water erosion (Zhao, 2006). The results from this study showed that the effects of different vegetation cover types on SOC stocks decreased in the following order: grass> shrub > tree > bare soil (Figure 2). In 30 years after vegetation reestablishment, SOC stocks at 0 to 10 cm depth on the slope under grass, shrub and tree cover were 0.42, 0.38 and 0.12 t C ha^{-1} yr^{-1}(Mg ha^{-1} yr^{-1}) higher than that of the bare soil, respectively. Lugo and Sanchez (1986) found that in Puerto Rico, SOC increased by 0.8 to 4.0 Mg ha^{-1} year^{-1} during secondary forest succession on land that had been cultivated for 100 to 300 years. Bouwman and Leemans (1995) reported that reforestation restored 50 Mg ha^{-1} of SOC in 30 years, giving a tentative estimate of global SOC accumulation rate in tropical tree plantations of 0.07 Pg year^{-1}. A much lower SOC storage rate from the present study in Southwest China than from the studies in other tropical regions (Lugo and Sanchez, 1986; Bouwman and Leemans, 1995) may be explained by the differences in soils, climate, vegetation and land management practices; however, an evident enhancement in SOC stocks by reforestation is the same for these studies. Six et al. (2002) suggested that trees may be less effective than shrubs and grasses in the study area at storing C in soil. This is in agreement with the present study.

Like SOC, AN contents in soil under shrub and grass cover were significantly greater than that under tree cover which was the same as in the bare soil (Figure 2). This can be explained by the differences in the ground cover structure among different vegetation types. Aboveground vegetation reduced water-induced soil erosion by intercepting rainfall, increasing water infiltration on associated soil-fertility islands, intercepting runoff at soil surface (Gyssels et al., 2005), retarding flow velocities by their stems and leaves as roughness elements (Styczen and Morgan, 1995), improving soil physical, chemical and biological properties (Casermeiro et al., 2004). Valentin et al. (2005) suggested that vegetation layer near soil surface must be more effective in intercepting rain drops than tall trees without under storey which can have higher kinetic energy and therefore favoring soil loss by water erosion. Such findings are in agreement with the results from the present study, that is, grasses and shrubs functioning as the intercepting vegetation layer had higher soil nutrients than that of the tree cover without intercepting vegetation layers, which resulted from the removal of leaf litters by local farmers for cooking. Furthermore, the effects of different vegetation cover types on retaining AP increased in the following order: bare soil < tree < shrub < grass. This suggests that a significant AP content in soil was effectively trapped by vegetations (grass, shrub, and tree) and lost in the bare soil due to water erosion and occasionally human interruption. Unlike SOC and AN, irrespective of slope positions, AP showed an increase trend in the downslope direction, particularly with more AP contents in the lower portion of the hillslope (Figure 3). These remarkable spatial pattern may reflect that AP is more easily fixed with fine soil particles than AN and SOC. AP and fine soil particles move on the hillslope by the same selective transport mechanism during water-induced soil redistribution and therefore deposited at the lower slope position (Li and Lindstrom, 2001).

Lower BD at 0 to 10 cm depth under shrub and tree cover than that under grass cover and bare soil BD may reflect a double effect of both vegetation cover types and grazing activities on physical properties of soil surface. Wu et al. (2009) also reported that BD in soil under shrub, tree and grass cover (1.17 to 1.21g cm^{-3}) was respectively reduced by 11% as compared with that in farmland (1.31 g cm^{-3}). A high BD at soil surface under grass cover and bare soil may partially be explained by the trampling effects of living stocks in grassy area and bare soil of the surveyed hillslope, evidenced by the track or path that formed along the eroded hillslope from the top to locations of water source (Figure 1). This explanation was supported by the research made by Gao et al. (2004) who reported that decrease in macropores (> 50 μM) and larger mesopores (9 to 50 μM) by increased living stocks trampling could lead to higher bulk density, greater penetration resistance and a decreased soil water holding capacity.

The results from the present study could partially be explained by our previous studies (Li et al., 1992a, b), where it was found that root systems, especially fibrous roots (diameter<1 mm), played a key role in maintaining soil structure, increasing soil permeability and organic matter content. Furthermore, Li et al. (1992a, b) found that grasses had the highest density of fibrous roots and followed by shrubs, being significantly higher than trees. This may explain why grass and shrub are more effective in maintaining soil structure and restrain soil nutrients loss than the trees. There are some other studies that also report the effects of roots of vegetation on soil erosion and associated nutrient loss. De Baets et al. (2007) reported that shrubs such as *Anthyllis cytisoides* (L.) and *Tamarix canariensis* (Willd.) had the highest root density in the topsoil, resulting in drastic reduction of soil erosion and thus soil nutrients loss. While not quantified as part of this study, it is likely that the mass of fibrous roots had increased with the re-vegetation project on this hillslope.

In conclusion, re-vegetation, specifically with shrubs and grasses, led to significant higher storage in surface SOC, AN and AP than that of the bare soil. No significant differences in SOC, AN and BD were found among different slope positions of the surveyed hillslope except for an increasing trend of AP content downward hillslope for its erodibility. Such results have important implications for the ecological restoration of eroded hillslopes in Southwest China. Further research is needed to look into the response of soil profile to different vegetation cover types that overlap and coexist along hillslope in Southwest China.

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