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Impacts of reforestation approaches on runoff control in the hilly red soil region of Southern China

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Summary Vegetation structure and soil properties are not only correlated with forest management practices, but also affect soil and water loss significantly. To estimate the long-term influences of regenerating forest cover on soil and water loss from degraded land, the runoff and soil loss in the context of different forest restoration approaches, including a control plot (CL) and plantations of slash pine (*Pinus elliottii*), Chinese fir (*Cunninghamia lanceolata*), tea-oil camellia (*Camellia oleifera*), and natural secondary forest, were monitored in runoff plots over a 4-year period (2000–2003) in a hilly red soil region in Southern China. Relevant ecological factors and management intensity, were also measured. The results indicated that the four forest restoration approaches decreased surface runoff by 63.0–88.1% and soil erosion by 75.5–97.1% compared to the control. Moreover, runoff and soil erosion in tea-camellia plantation (TCP) and natural secondary forest (NSF) plots were significantly lower than with other treatments. Canopy cover, litter fall, plant roots, plant life forms, soil properties, and vegetation structure are important ecological factors that determine the magnitude of soil loss. Vegetation structure and plant life forms are the main factors reducing surface runoff and the movement of sediments. Effective control of soil and water loss in NSF and TCP are closely related to multiply stratified communities and the presence of specific plant life forms (the herbaceous keystone species *Dicranopteris linearis*), respectively. In addition, the above mentioned factors were sensitive to forest management patterns, including improper mechanical cultivation. Management practices should attempt to minimize disturbances to these factors to control runoff and soil erosion in each forest management

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unit. In particular, mechanical cultivation should loosen the soil around the base of a tree only, instead of over the entire ground surface, in the early stages of forest restoration.

Introduction

Soil erosion causes a decrease in soil fertility and in the ability of the land to sustain plant growth. Since the canopy and litter can intercept raindrops and reduce their kinetic energy, vegetation cover becomes the main factor reducing surface runoff and the movement of sediments (Truman and Bradford, 1990; Deuchras et al., 1999). However, in a given area, different vegetation types, vegetation structure (canopy cover, sapling density, litter depth, and woody debris), plant species composition, and management practices can result in different intensities of soil and water loss (Casermeiro et al., 2004; Hartanto et al., 2003; Tian et al., 2003). Forest management practices can also bring about significant variability in vegetation structure, species composition, biodiversity, and soil properties (Ferris-Kaan et al., 1998; Zumeta and Ellefson, 2000; Larsson and Danell, 2001; Vanha-Majamaa and Jalonen, 2001; Paniagua et al., 1999; Fu et al., 2004; Zabinski and Gannon, 2007). Consequently, quantifying and understanding the effects of forest restoration approaches and management practices on vegetation structure and soil properties is especially important with regard to runoff and erosion control.

The formerly densely forested hilly red soil region of Southern China, which covers 2.18×10^6 km^2, including 10 provinces, is now known as the ''red desert of Southern China'' (Zhao, 2002). The effects of various agricultural uses on soil properties after deforestation have received much attention. Recent policies of ''returning farmland to forest'' in the middle and lower reaches of the Yangtze River have resulted in replanting of farmlands with slash pine, Chinese fir, tea-oil camellia, and other tree species. In a few areas, fallow farmlands have been left to undergo natural succession into secondary forest. In the tree plantations, mechanical cultivation, which makes the forest close up earlier and accelerates plant growth, was widely adopted in the area. However, little information is available on: (1) how vegetation structure and soil properties respond to forest restoration approaches and management practices, and (2) which key ecological factors (vegetation and soil) significantly affect runoff and erosion. Forest managers must limit disturbances to these factors to minimize soil erosion. Monitoring of soil loss using runoff plots was cost-effective and provided valuable information about soil erosion which allowed more direct linkages to be made between management practices and their impacts on runoff and soil erosion, thereby enabling forest managers to identify problems and take appropriate preventive measures to improve their management practices (Hartanto et al., 2003).

This study investigated the impact of reforestation approaches and management practices on vegetation structure, soil properties, surface runoff, and soil erosion at the plot level, with the following objectives: (1) to understand the effects of different reforestation approaches on vegetation structure and to provide a better understanding of the role played by soil surface features on the occurrence of runoff and erosion in the hilly red soil region of Southern China; (2) to assess the long-term impact of different forest restoration approaches on soil and water loss in the hilly red soil region of Southern China and to provide a conceptual basis for restoration practices; and (3) to investigate some of the possible consequences of future land-use changes for reforestation of the hilly red soil region. To achieve these objectives, the authors assessed the overall impact of four typical reforestation types (plantations of slash pine, Chinese fir, and tea-oil camellia, as well as natural secondary forest) on soil and water loss, by quantifying the vegetation structure, soil properties, surface runoff, sediments, and runoff process.

Study area and methods

Site description and experimental design

The study was conducted at the Ecological Benefit Monitoring Station of the Yangtze River Protection Forest, which is located in Hengyang County of southern Hunan Province (27°05′N, 112°18′E) (Fig. 1). Altitude in the area ranges from 86 to 147 m above sea level. A typical subtropical monsoon climate exists in this area, with an annual mean air temperature of 17.9 °C and an annual frost-free period of 340 days. Annual rainfall averages 1237 mm, concentrated during the period from May to August. The red soil of the area was formed from arenaceous shale and is approximately 100 cm thick. According to the Soil Taxonomy of China, this soil is classified as fine loamy, hyperthermic, and acidic Udic Cambisols (Gong, 1999).

In 1989, after all the existing vegetation had been removed by the local residents for firewood, four new forest stands were established: three plantations of slash pine (*Pinus elliottii*) (SPP), Chinese fir (*Cunninghamia lanceolata*) (CFP) and tea-oil camellia (*Camellia oleifera*) (TCP), respectively, and a naturally regenerated secondary forest (NSF). These forest stands are all located within an area of less than 1 km^2 and thus share similar topographic (slope and exposure) conditions. Edaphic conditions were similar in all stands before forest establishment (Table 1). Before revegetation, the three plantation areas were shaped into horizontal belts, and contour planting was used with standard dikes 100 cm wide and 50 cm high. Until 1998, the tree plantations were managed periodically (every 3—4 years) to maintain them as monoculture stands. Management practices included completely loosening the surface soil and clearing grasses and shrubs in the surrounding area. No fertilizer was ever applied. Plant residues generated in the cultivation process were normally left on the ground. The tea-oil camellia stand received less intensive management than the other two plantations, resulting in an extensive growth (125 individuals/m^2) of the herbaceous plant *Dicranopteris*

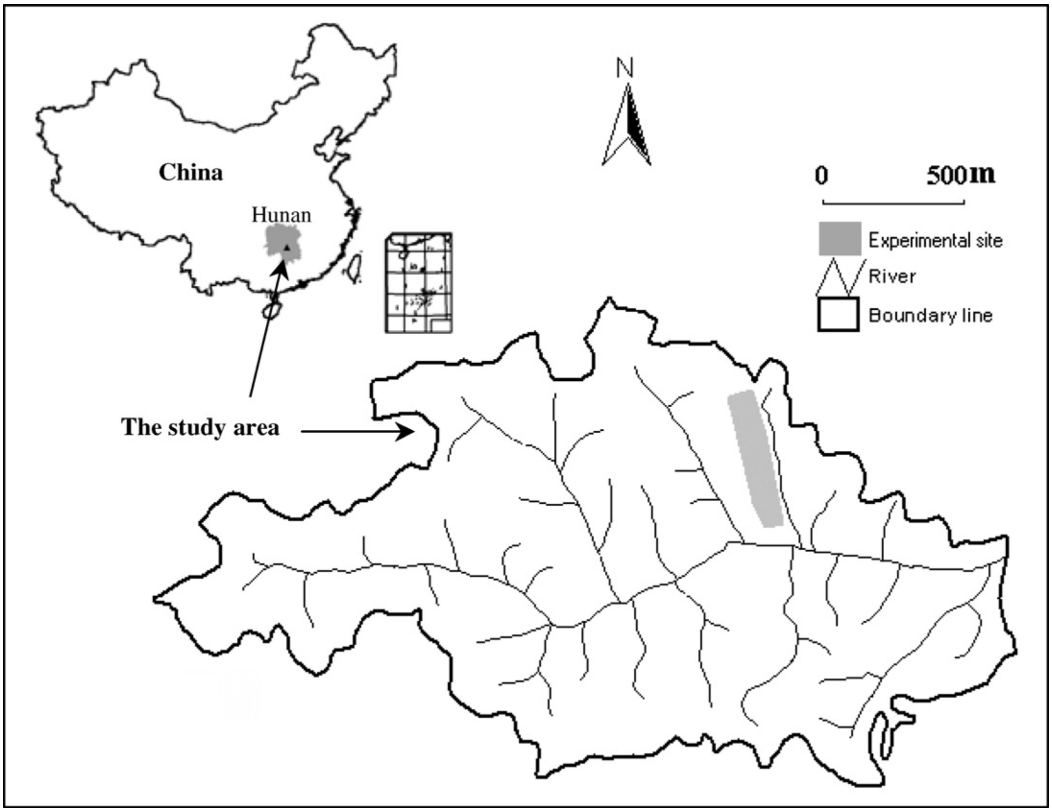

Figure 1 Location of the study area.

Table 1 Vegetation properties (0–20 cm depth) of experimental sites in 2003

Parameter	CL	SPP	CFP	TCP	NSF
Plant species richness	5	17	18	17	29
Coverage (%)	15	75	83	95	95
First layer (0–0.2 m) coverage (%)	12	25	30	80	38
Second layer (0.2–2.5 m) coverage (%)	3	30	40	70	60
Third layer (2.5–5.0 m) coverage (%)	–	15	30	15	80
Fourth layer (>5.0 m) coverage (%)	–	70	75	–	80
Average tree density (per ha)	–	2100	2967	2433	1400
Average DBH/BD* (cm)	–	10.7	7.7	2.6	10.3
Average tree height (m)	–	7.7	6.1	2.7	7.4
Leaf litter fall (t ha^{-1} yr^{-1})	–	3.74 (1.00) b	3.88 (1.07) b	5.75 (1.37) a	6.03 (1.59) a
Biomass of undergrowth plant layer (g m^{-2})	354 (29) d	1189 (222) c	1089 (313) c	1952 (382) b	3179 (393) a
Root biomass (g m^{-2})	338 (73) d	690 (180) c	1034 (280) b	1378 (352) a	1390 (367) a

CL, control; SPP, slash pine plantation; CFP, Chinese fir plantation; TCP, tea-oil camellia plantation; NSF, natural secondary forest.
Note: Standard deviations are provided in parenthesis. Values in same row followed by the same letter are not significantly different at $p < 0.05$ level.

* DBH/BD = diameter at breast height/basal diameter. For tea-oil camellia trees, the basal diameter was determined and the diameter at breast height was determined for other tree species.

linearis. The area where the natural secondary forest regenerated was closed to human activity in 1989, thereby preventing both disturbances by local residents and tree planting. This area has received no management and is currently dominated by tree species such as *Pinus massoniana*, *Cyclobalanopsis glauca*, *Quercus aliena*, and *Quercus fabri*. In addition, a site adjacent to a slash pine plantation was chosen as control (CL). At this site, local people fell firewood and graze all the time. Due to long-term over-exploitation and serious soil erosion, the vegetation coverage of some grass species, such as *Eragrostis pilosa*, *Imperata cylindrical*, *Miscanthus sacchariflorus*, was only 15%.

After planting, three 20 by 20 m plots were established at each forest site. Soils in each plot were sampled by depth

(0–20 cm, three replicate cores per plot along a diagonal transect) in April 1989.

Vegetation characteristics and plant sampling

The vertical distribution of plant species was studied in three plots for each site. Taking into consideration that in a typical subtropical forest, grasses are 20 cm tall, shrubs rise to 2.5 m, understory trees are 5 m tall, and canopy trees are >5 m tall, four different vertical layers were sampled: 0–0.2, 0.2–2.5, 2.5–5 and >5 m. Vertical layer boundaries were determined by visual estimation.

In July 2003, three $20 \times 20\ m^2$ plots were established at each forest site. Diameter at breast height (DBH), basal diameter (BD, only for tea-oil camellia whose height is less than 3 m), and height of all living trees were measured.

Understory biomass was also determined using destructive sampling techniques (total harvesting, including roots) within five randomly selected $2 \times 2\ m^2$ subplots within each $20 \times 20\ m^2$ plot. A total of fifteen $2 \times 2\ m^2$ plots were sampled in each forest type.

Leaf litter fall was sampled within six $1 \times 1\ m^2$ subplots randomly chosen in each $20 \times 20\ m^2$ plot. A total of 18 $1 \times 1\ m^2$ subplots were sampled in each forest type.

Runoff sampling

The experiments were performed in plots ($5 \times 20\ m^2$) marked out on the south slope of a hill. Three conjoint replications of plots were set up for each site, with 10-cm cement ridges projecting aboveground to isolate plot runoff and sediment. A discharge ditch was created at the top of each plot to divert runoff and sediments from the upper slope. At the base of each plot, two volumetrically calibrated tanks were arranged in series for runoff and sediment collection and were connected with a notch. Each tank was 1 m deep and 1 m in diameter.

During the 4-year monitoring period (2000–2003), soil loss and runoff from the plots were collected and measured in each tank after each rainfall event. The depth of runoff in each tank was measured, and 500 cm^3 of runoff water was sampled after stirring and mixing as soon as each runoff event ended. After measurement and sampling, the runoff water was drained and the tanks were cleaned. The runoff samples were filtered to measure sediment concentration on a dry basis. Sediment loss was calculated by multiplying the sediment concentration by the corresponding runoff volume. The sediment loss was referred to as the total soil loss, including both suspended and deposited soil losses.

As for the rainfall process, water samples were taken continuously from the beginning of the runoff event. During rainfall there stands a person beside each runoff plot, who records the time and the runoff every 5 min. Finally, the following parameters were calculated:

- time lag (the number of seconds from the beginning of the rainfall until the beginning of the runoff),
- runoff coefficient (the percentage of rainfall that becomes runoff),
- mean runoff ($ml\ s^{-1}$),
- peak runoff during the rainfall event ($ml\ s^{-1}$).

Rainfall measurement

An automatic rain gauge (0.2 mm per tip) and a standard manual gauge were installed at the summit (about 200 m from the plots). Rainfall events were separated by a minimum of one hour without rain. The rainfall data were collected from the rain gauge and standard manual gauge.

A large number of the identified rainfall events (44 in 2000, 40 in 2001, 33 in 2002, and 22 in 2003) had a high enough intensity for soil erosion to occur. The maximum rainfall in a single event for each year in the study was 81.5 mm on June 21, 2000, 113 mm on August 10, 2001, 92.4 mm on July 21, 2002, and 149 mm on June 27, 2003.

Soil sampling and analysis

In July 2003, three composite soil samples were collected from three replicate areas of CL, SPP, CFP, TCP and NSF to provide an adequate representation of site heterogeneity. Each composite sample is a mix of soil from five randomly selected locations along a diagonal transect within each of the $20 \times 20\ m^2$ plots. The soil was air-dried and analyzed for physical and chemical properties.

Soil bulk density (BD) was determined by the core method. Gravimetric water-holding capacity (WHC) of soil was measured by the tube method. Soil particle size analysis was performed using the hydrometer method. Total porosity was calculated according to particle density as determined earlier. The infiltration rate (IR) of the soil was measured by using a double-ring metallic infiltrometer with 35.5-cm outer diameter and 12.4-cm inner diameter, as described by Liu (1996). The analyses of soil physical properties were conducted in June 2002.

Soil pH was determined in a 1:2.5 soil-water slurry using a combination glass electrode. Soil organic carbon (SOC) was determined by the oil bath-$K_2Cr_2O_7$ titration method. Total nitrogen (TN) was determined by the semi-micro Kjeldahl method. Available nitrogen (AN) was determined by a micro-diffusion technique after alkaline hydrolysis. Total phosphorus (TP) was determined colorimetrically after wet digestion with $H_2SO_4 + HClO_4$. Available phosphorus (AP) was exacted with 0.5 mol/l $NaHCO_3$ solution (pH 8.5). Phosphate (P) in solution was determined colorimetrically by the formation of the blue phosphomolybdate complex following reduction with ascorbic acid. Total potassium (TK) was determined by the Cornfield method. Available potassium (AK) was determined by the CH_3COONH_4 extraction method (Liu, 1996).

Statistical analysis

'One-way analysis of variance (ANOVA) was used to compare the effects of various forest restoration approaches on properties of soil, runoff, and erosion. Values of soil properties that differed at $p < 0.05$ were considered significant trends. All the analyses were conducted using the SPSS 11.0 software.

Correlation coefficients and regressions were used to evaluate the effects of site factors on runoff and erosion in the different reforestation approaches. The variables considered were coverage, leaf litter fall, biomass of undergrowth plant layer, root biomass, soil bulk density, water holding capacity, sand, silt, clay, and porosity.

Results

Vegetation and soil properties

In the SPP, CFP, and NSF plots, average tree heights range from 6.1 to 7.7 m, and the average DBH, BD ranges from 7.7 to 10.7 cm. As an evergreen shrub, tea-oil camellia has the smallest average tree height and BD. This plant species is richer in NSF than in other forest types. Coverage is highest in the NSF and TCP plots and lowest in the CL plot. However, obvious differences were found between NSF and TCP when coverage was calculated by plant category (trees, shrubs, and herbaceous species). The coverage of the TCP plots is highest in the first and second vertical layers (0—0.2 and 0.2—2.5 m) and lowest in the third and fourth vertical layers (2.5—5.0 and >5.0 m). In the NSF plots, there exist four clearly defined layers with higher coverages (Table 1).

The biomass of the undergrowth plant layer in NSF was significant higher than in other forest types, and in SPP and CFP, biomass of this layer was significantly the lower. The trends for leaf litter were similar to those for the biomass of the undergrowth plant layer. Biomass of this layer was significantly lower in SPP and CFP than in TCP and NSF, but no significant difference was found between TCP and NSF.

Before forest establishment, edaphic conditions were similar in all the plots (Table 2). However, significant differences were observed among the five sites after reforestation (Table 2). Soils in the control (CL) and NSF plots had the highest and lowest bulk density, respectively. The values of porosity showed contrary trends to those for bulk density. Water-holding capacity was highest in the soils under natural secondary forest and lowest for the soils of the control site, but there was no significant difference in water-holding capacity among the three plantations. The soils of the plantations and the control site were considerably lower in silt and slightly lower in clay than adjacent soils under natural secondary forest. Sand content was lowest in the soils under natural secondary forest and significantly different from that of the other sites (Table 2).

The acidic soils in the study area resulted mainly from red soil evolution under conditions of high temperature and high humidity. The pH value of the soil in the control site was the highest, while the soils under the slash pine plantation were significantly more acidic than those of other forested sites. Soil organic carbon content showed the following ranking: natural secondary forest > Chinese fir plantation > tea-oil camellia plantation > slash pine plantation > control. It was significantly higher in natural secondary forest than in the plantations and the control site. Total nitrogen and total phosphorus showed the same trend as soil organic carbon. Total potassium content in soils under the Chinese fir plantation was the lowest. The soils under the tea-oil camellia plantation and the control sites had higher total potassium content, with values significantly different from those of natural secondary forest and Chinese fir plantation soils (Table 2).

Table 2 Soil properties (0—20 cm depth) of experimental sites in 1989 and 2003

Parameter	CL	SPP	CFP	TCP	NSF
Soil properties in 1989					
Soil bulk density (g cm^{-3})	1.36 (0.08) a	1.38 (0.15) a	1.37 (0.13) a	1.36 (0.11) a	1.36 (0.04) a
pH	4.60 (0.20) a	4.60 (0.17) a	4.60 (0.20) a	4.60 (0.30) a	4.70 (0.26) a
Soil organic carbon (g kg^{-1})	8.55 (0.77) a	9.71 (0.98) a	10.01 (0.93) a	9.88 (0.55) a	10.70 (1.14) a
Total nitrogen (g kg^{-1})	1.59 (0.10) a	1.54 (0.10) a	1.61 (0.07) a	1.58 (0.07) a	1.65 (0.08) a
Available nitrogen (mg kg^{-1})	156.49 (21.39) a	155.65 (6.10) a	159.34 (8.45) a	157.71 (14.99) a	162.78 (16.38) a
Available phosphorus (mg kg^{-1})	3.28 (0.41) a	3.25 (0.47) a	3.35 (0.38) a	3.30 (0.10) a	3.40 (0.12) a
Available potassium (mg kg^{-1})	98.84 (10.75) a	97.40 (6.55) a	98.66 (9.04) a	99.25 (17.7) a	102.52 (21.08) a
Soil physical properties in 2003					
Soil bulk density (g cm^{-3})	1.38 (0.05) a	1.28 (0.05) ab	1.21 (0.12) b	1.18 (0.05) bc	1.07 (0.05) c
Water-holding capacity (%)	23.67 (1.11) d	25.20 (0.55) cd	27.85 (0.40) b	26.95 (0.90) bc	33.40 (1.58) a
Sand (%)	66.16 (0.62) a	67.94 (0.57) a	58.61 (1.33) b	58.93 (7.40) b	48.36 (0.42) c
Silt (%)	16.56 (0.71) bc	13.90 (0.45) c	22.96 (1.87) ab	21.48 (8.73) abc	27.73 (2.79) a
Clay (%)	17.28 (0.21) b	18.16 (1.20) b	18.42 (0.74) b	19.59 (1.35) b	23.91 (2.94) a
Porosity (%)	40.25 (2.22) c	42.55 (2.10) bc	45.54 (2.93) b	46.11 (2.41) b	50.85 (1.52) a
Soil chemical properties in 2003					
pH	4.66 (0.05) a	4.22 (0.06) c	4.37 (0.13) b	4.54 (0.06) a	4.42 (0.09) b
Soil organic carbon (g kg^{-1})	3.21 (0.87) d	8.01 (0.41) c	10.67 (0.90) b	10.58 (0.73) b	14.10 (2.22) a
Total nitrogen (g kg^{-1})	0.34 (0.08) d	0.54 (0.01) c	0.73 (0.06) b	0.74 (0.02) b	1.00 (0.16) a
Total phosphorus (g kg^{-1})	0.14 (0.02) b	0.15 (0.02) ab	0.17 (0.02) ab	0.21 (0.03) ab	0.23 (0.09) a
Total potassium (g kg^{-1})	21.3 (0.45) a	20.10 (0.50) ab	15.97 (0.78) c	22.17 (2.21) a	18.73 (1.34) b
Available nitrogen (mg kg^{-1})	29.33 (4.62) c	41.00 (1.00) c	62.33 (5.03) b	64.00 (15.28) b	84.67 (17.68) a
Available phosphorus (mg kg^{-1})	0.26 (0.10) c	0.53 (0.18) bc	0.95 (0.04) ab	1.22 (0.23) a	0.83 (0.04) b
Available potassium (mg kg^{-1})	57.67 (5.33) b	70.45 (4.65) b	77.03 (18.18) b	91.47 (0.81) b	178.67 (48.92) a

Note: Standard deviations are provided in parenthesis. Values in same row followed by the same letter are not significantly different at $p < 0.05$ level.

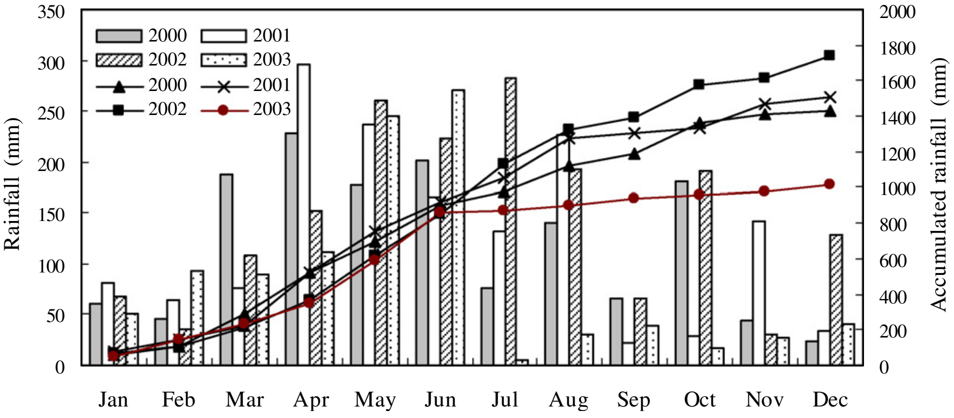

Figure 2 Distribution of rainfall and accumulated rainfall for 4 years (2000—2003).

Rainfall characteristics

During the study period from 2000 to 2003, annual rainfall averaged 1423.7 mm, with a minimum of 1019.3 mm in 2003 and a maximum of 1737.3 mm in 2002 (Fig. 2).

The rainy season lasted from April to August, and the rainfall during the rainy season accounted for 63.9—70.2% of annual rainfall. Monthly rainfall over 250 mm occurred in most of the years, except in 2000. The highest monthly rainfall amounts were 227.7 mm in April 2000, 296.7 mm in April 2001, 282.7 mm in July 2002, and 270.7 mm in June 2003 (Fig. 2).

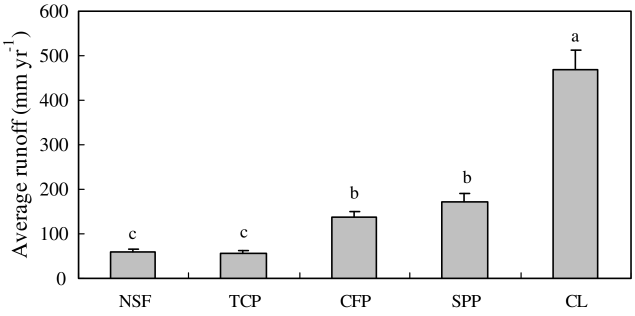

Figure 3 Average runoff of the five ecosystems for 4 years (2000—2003) (Note: Vertical lines denote standard deviations. Values followed by the same letter are not significantly different at $p < 0.05$ level).

Runoff and runoff process

During the study period, annual runoff from the five sites varied between 59.0 and 467.6 mm, corresponding to 4.1—32.8% of the annual rainfall.

In contrast with the control site, vegetation restoration on the degraded land decreased the average annual runoff by 294.6—408 mm during the study period. Among the five treatments, significant differences in average runoff were also found between CL and the other treatments, and the average runoff in CFP and SPP was significantly higher than that in NSF and TCP (Fig. 3).

The distribution of runoff basically follows the pattern of rainfall amount and intensity, with maximum monthly runoff occurring in June, irrespective of forest restoration type. Runoff was mainly concentrated in the period from April to August, which accounted for 70.4—80.8% of the average annual runoff (Fig. 4).

Fig. 5 and Table 3 show the average values of different hydrological parameters in each reforestation type during a specific rainfall event on June 29, 2002 (rainfall = 59.1 mm; rainfall time = 324 min; I_{30} = 10.4 mm/h). Such results must be considered for comparative purposes, that is, to see the different responses of different reforestation types and to arrive at some conclusions about the consequences of human

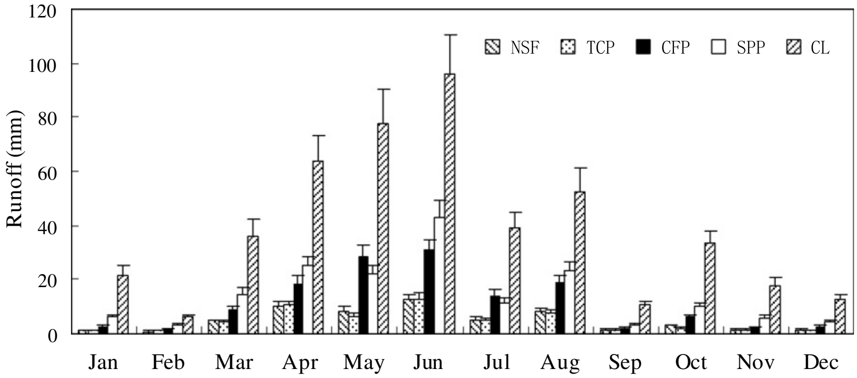

Figure 4 Monthly distribution of runoff for 4 years (2000—2003) (Note: Vertical lines denote standard deviations).

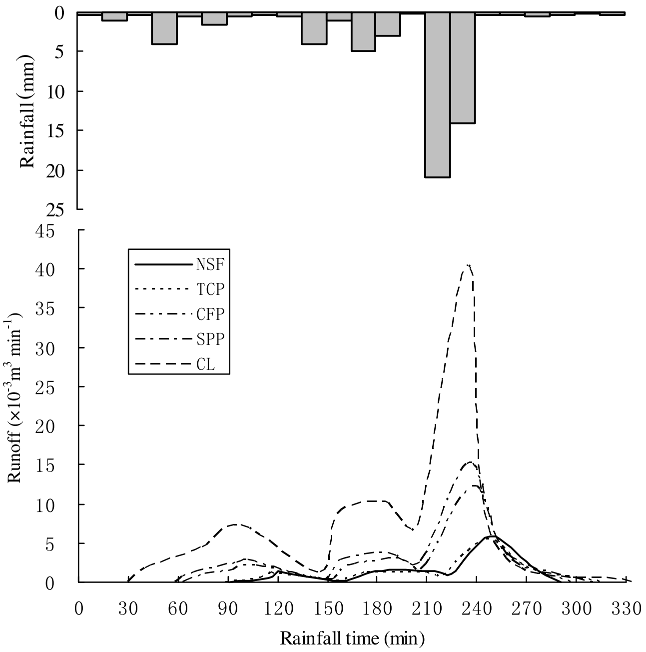

Figure 5 Rainfall-runoff flow hydrograph of the five ecosystems (June 29, 2002).

disturbance in the hilly red soil region as well as of forest management practices. The results obtained must not be used to calculate erosion rates, though some authors have arrived at predicted erosion figures using rainfall simulation (Young and Burnell, 1972). In all cases, striking differences have been observed between the reforestation approaches, and the results can be used to contribute to improved land management in the hilly red soil region.

The most important result is that the control plot exhibited the quickest response to precipitation, with runoff starting 30.4 min after the beginning of the rainfall event. The control plot also recorded the highest runoff coefficient values and the highest peak flow. The differences from the other reforestation types are especially dramatic in the case of time lag. The TCP and NSF plots showed a very long time lag (88.8 and 91.3 min) before the onset of runoff, and for the other hydrological parameters, their results were also outstanding. Finally, the TCP and NSF plots showed better results than other plots, with the lowest runoff coefficient and lowest peak flow. The SPP and CFP showed midrange values of the hydrological parameters (Table 3).

Erosion

Among the five treatments, significant differences were found for soil loss between CL and the other treatments. During the study period from 2000 to 2003, the annual soil loss in the control plot averaged 32.30 t ha^{-1}, about 4–7 times the loss in the CFP and SPP plots and about 26–35 times that in the NSF and TCP plots (Fig. 6). Soil loss was significantly greater under slash pine and Chinese fir than under tea-oil camellia plantation and natural secondary forest, which experienced less human disturbance. However, a significant difference in soil loss between the CFP and SPP plots was also found. Corresponding to the rainfall and runoff events, soil loss mainly occurred in the period from April to August, which accounted for 74.9–87.1% of mean annual soil loss, with the worst month being June (Fig. 7).

Factors affecting runoff and soil erosion

The results of correlation analysis showed that there were significant correlations linking runoff and soil loss with coverage, leaf litter fall, root biomass, soil bulk density, and porosity (Table 4).

Significant linear correlations between vegetation factors and soil properties were observed. Coverage, leaf litter fall, biomass of the undergrowth plant layer, and root biomass were significantly correlated with bulk density and porosity. Biomass of the undergrowth plant layer was also significantly correlated with water-holding capacity and with silt content, and there exists a significantly

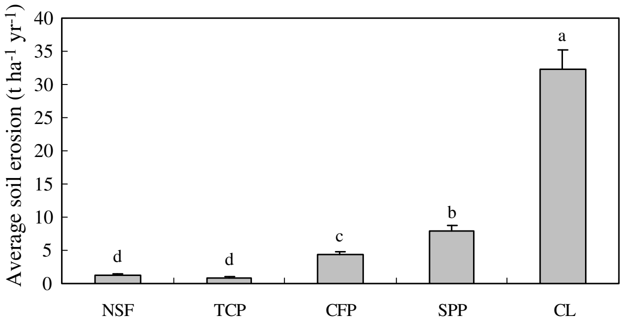

Figure 6 Average soil erosion of the five ecosystems for 4 years (2000–2003) (Note: Vertical lines denote standard deviations. Values followed by the same letter are not significantly different at $p < 0.05$ level).

Table 3 Mean results of a typical rainfall event

	CL	SPP	CFP	TCP	NSF
Runoff time (min)	305.6 (15.9) a	251.8 (25.1) b	252.3 (30.1) b	208.2 (20.3) bc	199.7 (27.6) c
Time lag (min)	30.4 (3.7) c	58.2 (10.3) b	62.7 (11.5) b	88.8 (10.7) a	91.3 (8.1) a
Peak flow (10^{-3} m^3 min^{-1})	40.4 (4.1) a	15.2 (1.9) b	12.2 (1.9) b	5.5 (1.1) c	5.9 (1.2) c
Mean discharge (ml s^{-1})	116.0 (23.4) a	50.9 (7.7) b	39.0 (8.8) bc	21.3 (6.4) c	25.6 (5.1) c
Runoff coefficient (%)	36.0 (3.6) a	13.0 (6.2) b	10.0 (2.6) bc	4.5 (2.2) c	5.2 (1.6) c

Note: Standard deviations are provided in parenthesis. Values in same row followed by the same letter are not significantly different at $p < 0.05$ level.

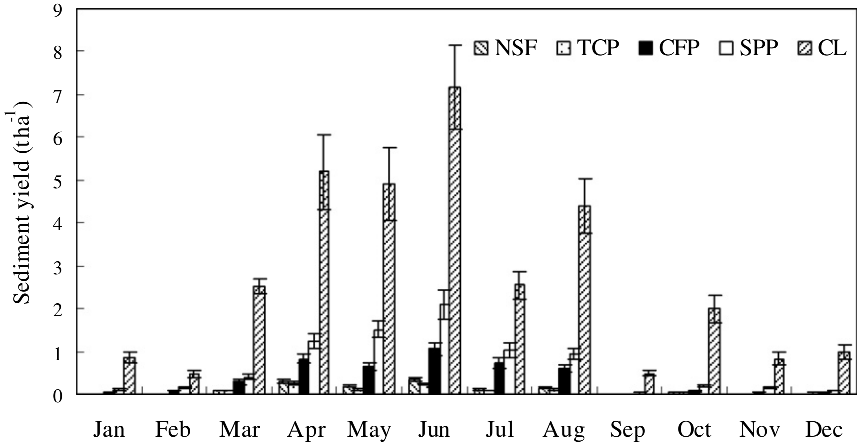

Figure 7 Monthly distribution of sediment yield for 4 years (2000—2003) (Note: Vertical lines denote standard deviations).

negative correlation between root biomass and sand content (Table 4).

Discussion

Vegetation structure and soil property variability induced by different reforestation approaches

Compared with CL, vegetation rapidly regenerated under the four reforestation approaches, as characterized by coverage, plant species richness, leaf litter fall, biomass of the undergrowth plant layer, and root biomass. And the regeneration of vegetation in the TCP and NSF plots was better than in the SPP and CFP plots, according to the following indicators: coverage, plant species richness, leaf litter fall, biomass of the undergrowth plant layer, and root biomass (Table 1). As for soils, similar trends exist among the CL, SPP, CFP, TCP, and NSF sites.

The differences in vegetation structure and soil properties among all the sites may be closely related to the degree of human disturbance. In the TCP and NSF sites, the number of vertical layers, leaf litter fall, biomass of the undergrowth plant layer, and root biomass were significantly higher than in the CL, SPP and CFP sites, which undergo land shaping and periodic mechanical cultivation. During reforestation, mechanical cultivation was an effective approach to make the forest close in earlier and accelerate plant growth, which was the initial motive of forest restoration. However, loosening the soils over the entire ground surface restrains the growth of undergrowth plants, breaks up macroaggregates, exposes previously protected organic matter in soil macroaggregates, and accelerates the mixing of organic residuals and soils, including land shaping. Because of mixing of organic residuals and soil and enhanced microbial activity, part of the organic matter decomposed, resulting in a degradation of soil structural properties and a resulting increase in bulk density (Blair et al., 1995).

According to Allen (1985), soil compaction commonly results in a decline in macroporosity, high susceptibility to erosion, and decreased hydraulic conductivity. These phenomena were observed in this study. For instance, bulk density, water-holding capacity, infiltration rate, and porosity of control and plantation soils were lower than those of natural secondary forest soils, as may result partly from periodic cultivation and land shaping (Table 1).

Consequently, in the early stage of forest restoration, altering these mechanical cultivation methods may be an effective way to protect soil and reducing human disturbance can accelerate the development of undergrowth plants, which play a key role in maintaining soil fertility, controlling soil erosion, and increasing forest productivity (Mo et al., 1997, 2002). In the present research, these results were confirmed (Table 2).

Effects of vegetation structure and soil property variability on runoff and erosion

Different degrees of human disturbance, including improper mechanical cultivation and land shaping, brought about differences in vegetation structure and soil properties (Table 1 and 2), which had a further impact on soil and water loss. Correlation analysis also showed that coverage, leaf litter fall, root biomass, soil bulk density, and porosity significant affected soil loss and runoff (Fig. 3 and 6; Table 4).

Canopy cover and litter depth appeared to be important ecological factors in determining the magnitude of soil loss. The tree canopy determines the size and erosive power of raindrops. The litter layer protects soil surface, thus preventing soil detachment, and provides surface roughness that minimizes soil particle movement down the slope and reduces runoff velocity (Hartanto et al., 2003; Casermeiro et al., 2004; Descroix et al., 2001). Ross and Dykes (1996) found that removal of the litter layer resulted in a 20-fold increase in runoff and soil loss compared to the intact forest floor. It is the litter layer, rather than the root mat, which provides the main protection for mineral soil and prevents rain splash and particle detachment. In the present study, the canopy cover and litter fall were the highest in the TCP and NSF plots, and soil and water loss was also significantly less severe in these plots. In fact, in the hilly red soil region of Southern China reforested areas often suffer from heavy human disturbance, foraging for firewood. This activity removes 34—46% of the total biomass each year and inhibits the growth of a shrub layer by harvesting the litter fall and the understory plants (Mo et al., 2004). Therefore,

Table 4 Spearman correlations between runoff, soil loss, rainfall, and ecological factors

Variables	Runoff	Soil erosion	Coverage	Leaf litter fall	Biomass of undergrowth plant layer	Root biomass	Soil bulk density	Water-holding capacity	Sand	Silt	Clay	Porosity
Runoff	1.000	0.995**	−0.999**	−0.986**	−0.784	−0.924*	0.885*	−0.695	0.633	−0.594	−0.637	−0.817*
Soil erosion		1.000	−0.999**	−0.964**	−0.732	−0.891*	0.855*	−0.664	0.590	−0.560	−0.583	−0.783
Coverage			1.000	0.977**	0.762	0.908*	−0.873*	0.685	−0.616	0.580	0.615	0.804
Leaf litter fall				1.000	0.867*	0.950**	−0.923*	0.750	−0.698	0.641	0.733	0.866*
Biomass of undergrowth plant layer					1.000	0.862*	−0.948**	0.920*	−0.874*	0.778	0.969**	0.949**
Root biomass						1.000	−0.943**	0.792	−0.821*	0.803	0.758	0.911*
Soil bulk density							1.000	−0.942**	0.913*	−0.866*	−0.902*	−0.991**
Water-holding capacity								1.000	−0.961**	0.907*	0.957**	0.973**
Sand									1.000	−0.982**	−0.917*	−0.957**
Silt										1.000	0.825*	0.912*
Clay											1.000	0.934*
Porosity												1.000

* Correlation is significant at $\alpha = 0.05$.

** Correlation is significant at $\alpha = 0.01$.

it is necessary for runoff and erosion control to exclude above human activity from plantations.

Plant roots can secure loose soil, increase the water-holding capacity of soils, hold soils against erosion (Greacen and Sands, 1980) and supply organic matter for soil. Ross and Dykes (1996) found that removal of the root mat resulted in a six fold increase in runoff and soil loss compared to the intact forest floor. In this study, small values of runoff and soil losses correspond with high values of root biomass, which lead to reduced erosion and runoff (Table 1; Figs. 3 and 6).

Soil structure was considered as one of the more important indicators of soil erosion (Barthès and Roose, 2002; Le Bissonais, 1996; Amezketa et al., 1996). It is closely related to the movement of water in the soil through physical properties such as water storage capacity, bulk density, and porosity (Truman and Bradford, 1990; Deuchras et al., 1999; Barthès and Roose, 2002). In addition, organic carbon increases the formation of soil aggregates (Casermeiro et al., 2004). Descroix et al. (2001) also found that soil organic matter content was negatively correlated with runoff and soil loss, while sand content increased runoff and erosion, and higher silt content resulted in good structural stability leading to reduced erosion and runoff. By contrast, in this research, the soils of the plantation and control plots were considerably lower in silt and slightly lower in clay than adjacent soils under natural secondary forest, most likely as the result of preferential removal of silt and clay by accelerated water erosion (Hassan and Majumder, 1990).

Plant life forms and vegetation structure influence the level of protection provided against erosion. In the present research, it was found that TCP and NSF can control soil and water loss effectively and to a significantly greater extent than CL, SPP, and CFP. However, the plant species richness is only 2, and there are only two obvious layers (0—0.2 m and 0.2—2.5 m) in the TCP plots. Areas dominated by grassy plants such as *D. linearis* (average 125 individuals per square meter) in the TCP plots are the most effective at avoiding erosion. Other studies also reported that low values of runoff and soil loss correspond with high values of grass cover (Descroix et al., 2001). And the types of plant life forms were also found to be influential to runoff control (Casermeiro et al., 2004). Whereas in the NSF plots, the plant species richness is 14, and there are four obvious vegetation layers (0—0.2, 0.2—2.5, 2.5—5.0, and >5.0 m). Vegetation structure may be the main factor influencing soil and water loss. Multiply stratified areas are more efficient than mono-stratified areas at avoiding erosion (Casermeiro et al., 2004). And understory vegetation such as saplings and seedlings provides a second layer of protection to the soil. Their canopies, which are located closer to the soil surface than tree canopies, can further reduce the erosive power of the raindrops (Wiersum, 1984; Sinun et al., 1992).

Implications for management and forest restoration

After 14 years, all modes of forest restoration on degraded red soils were successful. The better soil and water conservation achieved in the tea-oil camellia plantation results mainly from the presence of the fast-growing herbaceous plant, *D. linearis*. As to natural secondary forest, its beneficial effect on soil and water conservation can be attributed to its multiply stratified vegetation structure. Therefore, the role of herbaceous plants and a multiply stratified vegetation structure is very important for controlling soil and water loss. Their ecological characteristics could be effectively used according to plant community composition under various geographic conditions. The benefits of selecting excellent native species to control soil erosion should not be neglected.

The common characteristic of the two forest types was that they experienced little or no human disturbance during vegetation restoration. Improper mechanical cultivation and land shaping would have influenced not only canopy cover, litter fall, plant roots, and understory vegetation, but would also have impacted soil properties. However, the processes of natural succession also demonstrate that nature can achieve restoration unaided and develop fully functioning soils (Bradshaw, 1997). As for plantation management, mechanical cultivation that loosens the soil over the entire ground surface should be replaced by loosening the soil around the base of the trees only. This change will benefit the restoration of undergrowth plants and the conservation of soil and water.

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